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Utility-Interfaced High-Frequency Flyback Transformer Linked Sinewave Pulse Modulated Inverter for a Small Scale Renewable Energy Power Conditioner

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ABSTRACT

This paper presents a novel prototype of the utility AC power interfaced soft-switching sinewave pulse modulated inverter using the high-frequency flyback transformer for the small scale distributed renewable energy power conditioner. The proposed sinewave power conditioner circuit with a high-frequency isolation link has a function of electrical isolation, which is more cost-effective and reliable for the small-scale distributed renewal energy utilization system from a safety point of view. The discontinuous conduction mode (DCM) operation of the high-frequency flyback transformer is adopted to establish a simple and low-cost circuit configuration and control scheme. For the simplicity, the circuit operating principle is described on the basis of the modified conventional full bridge inverter, which is the typical conventional high-frequency full-bridge inverter employing the high frequency flyback transformer to enable the effective function of the electrical isolation. Then, the new circuit topology of the utility-interfaced soft-switching sinewave pulse modulated inverter using IGBTs is proposed. The proposed circuit topology is additionally composed of the auxiliary power regenerating snubber circuits, which are also mathematically analyzed for the purpose of the parameter design settings. Finally, the performance of the proposed inverter is evaluated on the basis of computer-aid simulation. It is noted that the sinewave pulse modulated output current of the inverter is synchronous to the AC main voltage.

Key Words: Flyback transformer, High-frequency isolation link, Discontinuous conduction mode, Power regenerating snubber circuit, Utility-interfaced sinewave PWM inverter, Renewable energy power conditioner

1. Introduction

In recent years, there are many continuing efforts to develop and commercialize the distributed electrical power generators using the new clean and small-scale energy resources from an earth environmental point of view.

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Especially, the small-scale solar photovoltaic(PV) power generating system and small-scale fuel cell for residential applications become significantly practical. In addition to this, the development of the 3kW-5kW fuel cell systems is also nearly practical and acceptable for being used as the utility interactive distributed power supplies. These trends mean that more PVs and fuel-cell power generators will be able to be widely used as the distributed power generating systems connected to the utility AC power grid through the typical inverters for power conversion conditioning processor. However, in case of employing a fuel-cell power conditioning system in the DC side or connecting a PV power conditioning system with the utility power grid, the difficulty of the electrical insulation and the concern of safety cannot be neglected from a practical point of view. The function of the electrical isolation can be required for preventing the leak of DC components to the AC side, reducing the effect of the earth fault in the battery side and protecting the PV or fuel-power generator from lightning surges. As a result, the isolated transformers are commonly employed within the sinewave PWM inverters for isolating the static power generators from the utility AC power linked grid.

Typically, the utility-interfaced voltage source type inverters using MOS gate power semiconductor devices such as MOSFETs, IGBTs and MCTs in additional to the other semiconductor devices; SITs, B-SITs are installed with the transformers to isolate and protect the renewable power sources if the electrical isolation is needed. Although the transformers can prevent the leak of DC components and can be easily installed with the utility AC power grid connection, they are usually large and heavy. Also, the transformers occupy significant power losses to degrade the inverter efficiency. Moreover, the utility-interfaced high-frequency transformer link sinewave inverter for the renewable energy utilization system is still complex and requires the particular control scheme for delivering the gate controlled signals to the switching power semiconductor devices so that the output current can be synchronously in-phased with the utility grid voltage sinusoidally[2]. To reduce the power losses, the size and the weight of the transformers and to ease the complexity of the control circuit scheme with a sensor interface, the high-frequency transformer has been effectively introduced to electrically isolate the DC source from the utility AC side.

To provide the practical and effective solutions of the problems mentioned above, this paper proposes a novel circuit topology of the isolated and utility-interfaced sinewave PWM inverter using the high-frequency flyback transformer and incorporating the energy regenerating passive snubber circuits to achieve the soft-switching operations. Both the power conversion efficiency improvement and the downsizing of the power conditioning system are able to be achieved by incorporating the two or four active power switches type sinewave pulse modulated inverter with the high-frequency flyback transformer operated under the discontinuous conduction mode (DCM) The DCM operation is to prevent the main active power switches turn-on power losses. The additional passive snubber circuits connected in parallel with the active power switches are to regenerate snubber energy toward the DC supply source and reduce turn-off power losses of the active power switching operations. Furthermore, since the snubber power regenerations are completed passively, the circuit control implementation is as simple and cost-effective as the other conventional types of the isolated high-frequency flyback transformer linked sinewave inverter with two-switch or four-switch bridge topology.

In this paper, a typical non-isolated sinewave pulse modulated inverter in the reference [1] is modified by implementing the high frequency flyback transformer to isolate the DC source from the utility AC power side. The modified sinewave inverter circuit is presented along with the fundamental principle to be compared with the proposed inverter circuit topology, which is a new two-switch high-frequency flyback transformer linked sinewave pulse modulated inverter with the additional snubber circuit.

In this paper, the new power conversion circuit topology is able to be operated under the same basic principles of the modified conventional inverter. However, the additional snubber circuits enhance the operation of soft-switching turn-off commutations. In order to determine the circuit parameters of the proposed sinewave inverter for the computer simulation analysis, the state equations of the voltage and current of the additional passive snubber circuits are also derived. Finally, the validation of the proposed sinewave inverter circuit system is confirmed on the basis of the computer-aided simulation.

The operating characteristics of the sinewave pulse width modulation (PWM) switching operations and the utility output current are evaluated from an application point of view. The waveform of the output current indicates that high power factor with low distortion can be achieved. The captured switching voltage and current waveforms also illustrates that turn-on and turn-off switchings based on PWM controlled gate signals are operated under soft-switching conditions.

2. High-Frequency Linked Sinewave Inverter Type for Power Conditioner

2.1 Circuit description

Fig. 1 shows the utility-interfaced high-frequency link isolation-type sinewave pulse modulated inverter using IGBTs, which is modified from the conventional non-isolated high-frequency sinewave pulse modulated inverter in the reference. A high-frequency flyback transformer *MT* is employed to isolate the DC sources such as solar photovoltaic panels or fuel cells from the utility AC grid connection. The sinewave processing inverter with a high-frequency transformer link is operated by the discontinuous conduction mode (DCM) to generate the sinusoidal output current, which is synchronized with the grid voltage of the utility power system. The turn-on pulse sequences of the inverter full bridge active power switches (T_{u1}, T_{u2}, T_{v1}, T_{v2}) are determined by comparing the sinewave signal generated from the utility AC voltage waveform *e* with the frequency-specified sawtooth signal.

When the transformer primary-side active power switches are turned on, the magnetic energy is stored into the winding and is released to its secondary side as soon as the active power switches are turned off. In the utility AC side, either the power switch T_{Sp} or T_{Sm} is conducted to determine the polarity of the output current. That is, the utility AC-side switching devices are turned on and off every time that the polarity of the utility grid voltage has changed. For example, when the polarity of the utility grid voltage *e* is positive ($e>0$), only the transformer primary-side power switches T_{u1}, T_{v2} are actively controlled and only the utility AC-side switch T_{Sp} is conducted. On the other hand, the actively controlled power switches are vice

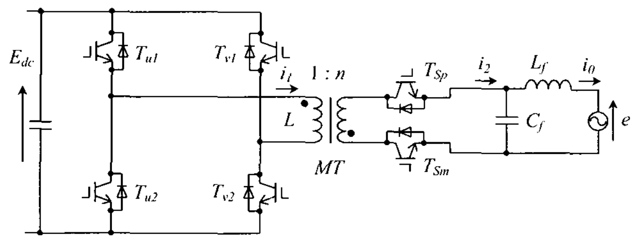


Fig. 1. The modified high-frequency flyback transformer link sinewave PWM inverter using IGBT power modules.

versa when the polarity of the utility grid voltage *e* is negative ($e<0$) and only the utility AC-side active power switch T_{Sm} is conducted. The low-pass filter (L_f, C_f) isconstructed in the utility AC side in order to smooth the discontinuous triangular current waveform into the continuous sinusoidal current to be injected in the grid connection of the utility AC power.

2.2 Control signal and circuit operation sequences

Fig. 2 illustrates the operating modes and equivalent circuits when the utility grid AC voltage *e* is positive ($e>0$). In case of the negative grid voltage *e*, the operating modes can be explained similarly by changing the active switches vice versa. Each mode can be explained as follows:

■ Energy Storage Mode (T0 ≤ t ≤T0+Ton)

Fig. 2 (a) represents the operating mode and equivalent circuit of which the utility grid voltage *e* is positive.

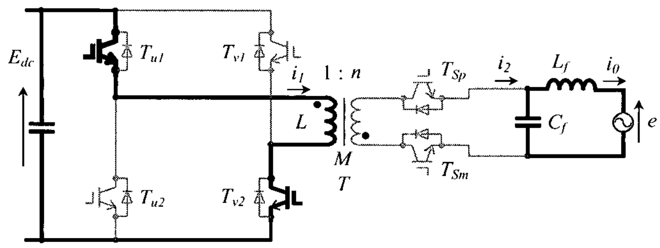
The active power switch T_{Sp} is conducted during every sampling cycle T_S of this period in order to deliver the positive output current. This mode begins when the main active power switches T_{u1} and T_{v2} are turned on at the beginning point T_0. The primary current i_1 flows into the primary winding of the high-frequency flyback transformer. The current i_2 is supposed to flow from the dot of the transformer secondary winding according to the characteristic of the flyback transformer but blocked by the wheeling diode of the active power switch T_{Sm}. Therefore, the energy is forced to store into the primary winding of the flyback transformer. According to the given initial conditions that $t=T_0$ and $i_1=0$, the transformer primary current and the secondary current of the flyback transformer can be obtained as follows,

$$i_1 = E_{dc}(t - T_0) / L \tag{1}$$

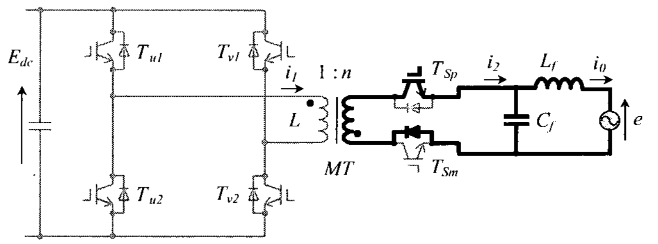
$$i_2 = 0 \tag{2}$$

Consequently, at the time $t=T_0+T_{on}$, the DC bus line side peak current can be given by

$$I_1 = T_{on} E_{dc} / L \tag{3}$$



(a) Turn-on mode of DC side active power switches T_{u1} and T_{v2}



(b) Turn-off mode of DC side active power switches T_{u1} and T_{v2}

Fig. 2. Operating modes and equivalent circuits.

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

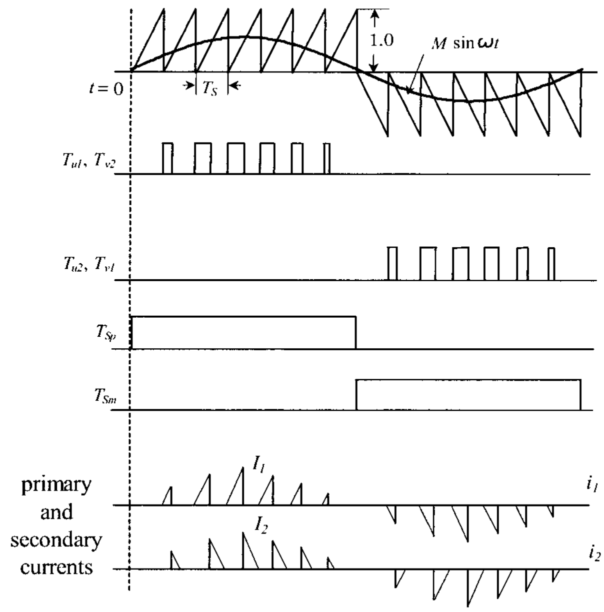
Fig. 2 (b) depicts the operating mode and equivalent circuit when the active power switch T_{u1} and the active power switch T_{v2} are turned off. The energy stored during the previous operating mode is suddenly released through the loop consisting of the diode of the active power switch T_{Sm} and the conducted active power switch T_{Sp} into the low-pass filter. Since the utility grid AC voltage is represented as $e = E_m \sin \omega t$ and the switching time T_S as the carrier sampling time is very small in practice, the utility grid AC voltage can be estimated to be uniformly fixed at $e = E_m \sin \omega T_0$ in any sampling cycle that starts at time T_0. In accordance with the initial conditions that $t=T_0+T_{on}$ and $i_2=I_2=I_1/n$, the currents at both sides are found as

$$i_1 = 0 \tag{4}$$

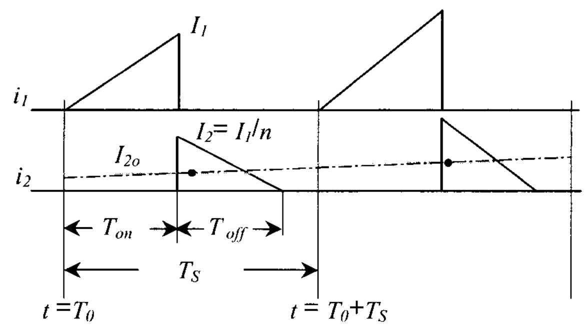
$$i_2 = I_2 - (t - T_0 - T_{on})\frac{E_m \sin \omega T_0}{n^2 L} \tag{5}$$

In accordance with the required condition of DCM, $i_2=0$ at the time $t=T_0+T_{on}+T_{off}$. Hence, the initial peak value I_2 becomes

$$I_2 = \frac{T_{off} E_m \sin \omega T_0}{n^2 L} \tag{6}$$



(a) Gate control pulse signals



(b) Current waveforms at the primary and the secondary side of the flyback transformer

Fig. 3. Control signals and current waveforms.

Fig. 3 shows the gate pulse signals and the current waveforms in the DC and AC sides of the high-frequency flyback transformer. The turn-on gate pulse signals delivered for DC-side active power switches (T_{u1}/T_{v2} or T_{u2}/T_{v1}) are generated by forming a sinusoidal waveform $M\sin\omega t$ based on the utility grid AC voltage e and comparing it to a synchronized sawtooth carrier signal. The gate pulse signal sequence of the active power switches T_{Sp} and T_{Sm} in the utility AC power side is synchronous to the low comercial frequency of the utility grid voltage e. To explain the timing pulse sequence of all the switch control signals, it is supposed that the grid voltage e is started with the frequency of 60Hz in Fig. 3 (a).

After being compared to the sawtooth carrier signal waveform, the positive first-half cycle waveform of the utility grid voltage e produces the PWM turn-on gate signal for DC-side active power switches T_{u1} and T_{v2}. The transformer secondary-side active power switch T_{Sp} is conducted during this period. For the negative second-half cycle, the PWM pulse signal is produced for the power switches T_{u2} and T_{v1} instead to change the current direction and the transformer secondary-side switch T_{Sm} is conducted to release negative current i_2 as illustrated in Fig. 3 (b).

Fig. 3 (b) magnifies the current waveforms in the DC and AC sides of the sinewave processing inverter. The sinewave pulse modulated inverter with a flyback transformer is designed to bring the current in the AC side to zero within any sawtooth carrier switching cycle T_S so that the current in the DC side rises from zero in the next switching cycle. I_{2o} is the average value of the triangular current i_2 within the switching cycle T_S and is equal to the output current being passed from the low-pass filter to the utility grid AC power connection.

3. Principle of Steady State Operation

On the basis of discontinuous conduction mode, the operating conditions of the sinewave pulse modulated inverter are established. Given that the switching frequency of carrier signal is high enough, the utility grid voltage is estimated to be uniformly fixed at $e = E_m \sin\omega T_0$ for any carrier switching cycle starting from time T_0 and the voltage across filter capacitor C_f is approximated to be the same as the voltage of the utility grid connection. Base on these conditions when the utility voltage $e>0$, the energy storing and releasing time can be respectively obtained from the equations (3) and (6) as:

$$T_{on} = \frac{LI_1}{E_{dc}} = \frac{nLI_2}{E_{dc}} \tag{7}$$

$$T_{off} = \frac{n^2 LI_2}{E_m \sin\omega T_0} \tag{8}$$

From the above equations, yields

$$I_2 T_{off} = \frac{E_{dc}^2 T_{on}^2}{LE_m \sin\omega T_0} \tag{9}$$

Therefore, for any carrier switching cycle T_S, the average of the output current i_2 denoted as I_{2o} becomes:

$$I_{2o} = \frac{I_2 T_{off}}{2T_S} = \frac{E_{dc}^2 T_{on}^2}{2T_S LE_m \sin\omega T_0} \tag{10}$$

Furthermore, the time T_{on} can be obtained from a principle of sinusoidal pulse width modulation as $T_{on} = T_S M \sin\omega T_0$. Then, the above equation yields:

$$I_{2o} = \frac{T_S E_{dc}^2 M^2 \sin\omega T_0}{2LE_m} \tag{11}$$

Consider the flyback transformer secondary-side current flowing through the low-pass filter, a sinusoidal current i_o synchronous to the AC grid voltage e is achieved and its rms value is determined by:

$$I_{2orms} = \frac{T_S E_{dc}^2}{2\sqrt{2}LE_m} M^2 \tag{12}$$

Next, it is important to establish some conditions so that the secondary current of the flyback transformer decreases toward zero within any sawtooth carrier switching cycle T_S to maintain the discontinuous conduction. Given that $T_{on}+T_{off} < T_S$, yields:

$$n^2 LI_2 \left(\frac{1}{nE_{dc}} + \frac{1}{E_m \sin\omega T_0}\right) < T_S \tag{13}$$

Since $I_2 = T_S E_{dc} M \sin\omega T_0 / nL$ the following condition is established as:

$$M\left(1 + \frac{nE_{dc}}{E_m}\right) < 1 \tag{14}$$

By arranging the peak value I_2 and the average value I_{2o} of the current in the AC utility side, it is obtained as follows:

$$2(1 + E_m / nE_{dc}) < I_2 / I_{2o} \tag{15}$$

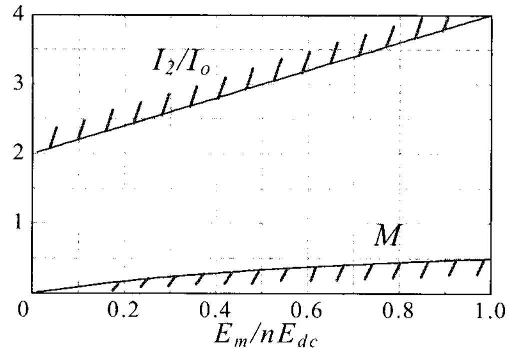


Fig. 4. Peak current and modulation index for flyback transformer turn ratio.

On the condition that the magnetized energy being stored in the primary winding with a magnetic-ferrite core of the high-frequency flyback transformer is completely transferred to the grid connection for every switching cycle T_S, it is required that $nE_{dc} > E_m \sin \omega T_0$ or,

$$nE_{dc} > E_m \tag{16}$$

Equations (14), (15) and (16) are visualized in Fig.4. From equation (16), it is obvious that $E_m/nE_{dc} < 1$ which forces the modulation ratio M to be operated under M=0.5. When the winding turn ratio of the flyback transformer is large, which results in the small operable modulation ratio M, the peak of the output current becomes small. However, small modulation ratio M causes a narrow PWM pulse width, which results in the peak current in the DC side of this inverter to become larger. Therefore, the balance of the peak currents in both sides of the flyback transformer has to be accounted for determining the winding turns ratio.

4. A Two-switch High-frequency Flyback Transformer Linked Soft-Switching Sinewave Inverter with Snubber Passive Energy Regeneration Circuits

4.1 Circuit description

The modified conventional circuit topology mentioned in the previous section is operated under the condition of DCM. The active power switches are turned on when the energy at the primary winding of the transformer is totally transferred to the transformer secondary winding.

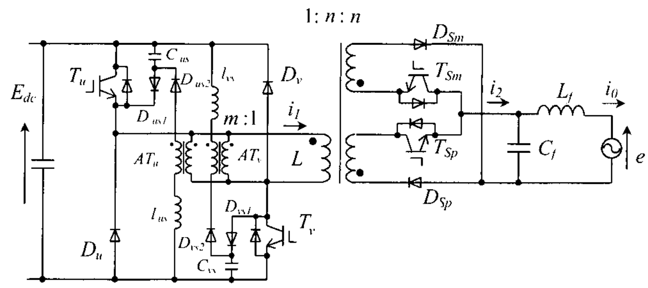


Fig. 5. Flyback transformer linked high-frequency soft-switching sinewave inverter using energy regenerating snubber circuit.

Therefore, they are turned on on the basis of zero current soft-switching commutation. However, they are forced to turn off under hard-switching condition to satisfy the PWM gate controlled pulse signals. In this section, we propose a revised circuit topology of the sinewave pulse modulated inverter with the power energy regenerating snubber circuits connected to the power switching bridge arms in parallel. With the additional passive power regenerating snubber circuits, the commutation operation of soft-switching turn-off is able to be realized. Fig. 5 illustrates the high-frequency flyback transformer linked sinewave pulse modulation inverter with the energy regenerating snubber circuits for utility-interfacing, which has some advantages such as reducing current leak and dv/dt and di/dt related noises and suppressing switching losses. The structure of the proposed sinewave processing circuit is mainly composed of two DC-side active power switches and the three-winding high-frequency flyback transformer. The active power switches T_u and T_v are connected with the snubber capacitors (C_{us}, C_{vs}) and the diodes (D_{us1}, D_{vs1}) in parallel positions. When these active power switches are turned on, the energy stored into the snubber capacitors is regenerated to the DC input side due to the rising voltages across the auxiliary high-frequency forward transformers (AT_u, AT_v) and the voltages across the supply voltage regenerating-assisted inductors (l_{us}, l_{vs}). Similar to the operation of the modified conventional sinewave processing inverter circuit mentioned previously, the AC-side active power switches T_{Sp} or T_{Sm} are being actively switched in accordance with the polarity of the utility grid voltage e. Two windings of the high-frequency flyback transformer are implemented in the AC side for the purpose of the polarity selection scheme. Both the proposed sinewave processing inverter circuit with two power regenerating feedback circuits and the modified conventional inverter circuit have the same number of the power semiconductor devices in the active power circuit paths. Thus, they generate similar amount of the conducting power losses. However, the active power switches of the sinewave pulse modulated inverter circuit with the energy regenerating snubbers are turned off under the principle of the zero voltage soft-switching mode transition. Therefore, the efficiency of the whole sinewave processing inverter system can be significantly improved from a practical point of view.

4.2 Soft-switching circuit operation

The energy regenerating operating mode when the grid voltage e is positive ($e>0$) are described below.

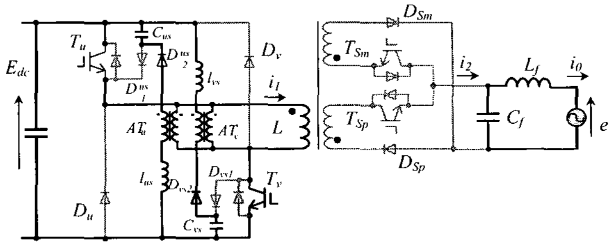
■ Energy Storage Mode ($T_0 \le t \le T_0+T_{on}$)

Fig. 6 (a) shows the operating mode that begins when the DC-side active power switches (T_u, T_v) are turned on, including the equivalent circuit. The snubber capacitors are charged to the voltage V_{S0} specified from the previous mode. The active power switch T_{Sp} is conducted for producing positive output current. In case of the negative output current is required, the active power switch T_{Sm} will be alternatively used.

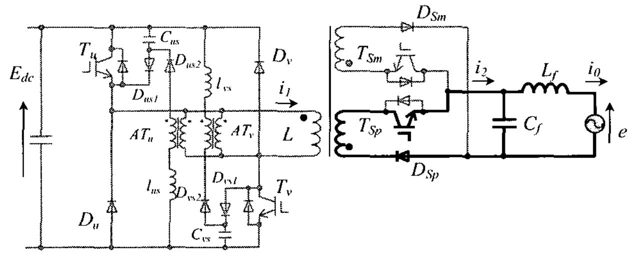
In this operating mode, the energy is stored into the primary winding of the high frequency flyback transformer. Simultaneously, the snubber capacitors resonate with the regenerating inductors and discharge their electricity due to the conduction of the diodes D_{us2} and D_{vs2} as the passive power switches with the aid of the rising voltages across the auxiliary high-frequency transformers and its primary winding. Since the active power switches are turned on when the magnetized energy of the high-frequency flyback transformer is completely zero, the zero current soft-switching turn-on operations (ZCS) are to be achieved. After the snubber capacitors are completely discharged and the primary current reaches the required level, the main active power switches will be turned off. Thus, they are operated under the principle of zero voltage soft-switching turn-off commutation assisted by the snubber capacitors.

■ Energy Release Mode ($T_0+T_{on} \le t \le T_0+T_{on}+T_{off}$)

Fig. 6 (b) illustrates the operating mode when the DC-side active power switches (T_u, T_v) are turned off, including the equivalent circuit. The energy stored into the primary winding of the high-frequency flyback transformer is suddenly released into its secondary winding through the loop path that includes the diode D_{Sp} as the passive power switch and the AC active power switch T_{Sp}. Similarly, when the grid voltage e is negative ($e<0$), the AC-side switch T_{Sm} is conducted instead of T_{Sp} to allow the negative output current to flow.



(a) Turn-on mode of DC side active power switches Tu and Tv



(b) Turn-off mode of DC side active power switches Tu and Tv

Fig. 6. Operating modes of energy regenerating snubber and each equivalent circuit.

Fig. 7 illustrates the control signal pulse sequences of the sinewave pulse modulated processing and conditioning inverter with two passive energy regenerating snubber circuits. By comparing the sinusoidal reference signal with the sawtooth carrier signal, the DC-side active power switches (T_u, T_v) are turned on and off in accordance with the gate pulse time T_{on} which depends on the utility grid voltage e.

4.3 Energy regenerating snubber circuit and analysis

Fig. 8 depicts the basic equivalent circuit of the energy regenerating snubber circuit operated when the DC-side active power switches T_u and T_v are turned on.

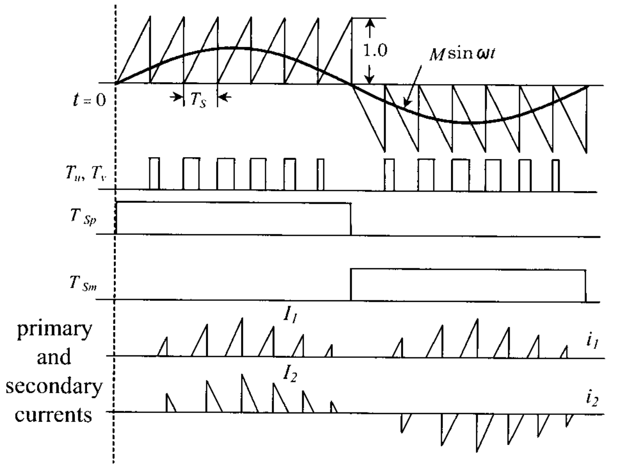


Fig. 7. Control signal of soft-switching sinewave pulse modulated inverter.

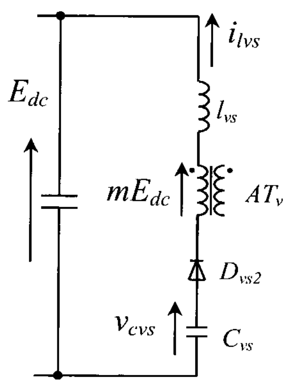


Fig. 8. Energy regenerating snubber circuit.

The auxiliary forward pulse transformers AT_u and AT_v, which are connected in parallel with the primary winding of the high frequency flyback transformer, generate the voltages mE_{dc} in the snubber circuits where m is the winding turns ratio of the auxiliary forward pulse transformers. According to the magnetized voltage mE_{dc}, the voltages v_{cus} and v_{cvs} of the snubber capacitors resonate with the resonant inductors l_{us} and l_{vs} respectively to regenerate the energy to the input supply voltage in DC bus line by discharging the capacitor storage energy. The circuit state equations are expressed as follows:

$$v_{cvs} + mE_{dc} - l_{vs}\frac{di_{lvs}}{dt} = E_{dc} \tag{17}$$

$$\frac{dv_{cvs}}{dt} = -\frac{1}{C_{vs}} i_{lvs} \tag{18}$$

At the end of the gate turn-on pulse signal, the active power switches are turned off under the principle of zero voltage soft-switching (ZVS) since the voltage across the capacitor C_{vs} and C_{us} are completely discharged. It is noted that at the time $t=0$, the initial voltage and initial current of the state variables are given as $v_{cvs} = V_{S0}$ and $i_{lvs} = 0$. Then, the voltage of the snubber capacitors and the regenerative currents becomes:

$$i_{lvs} = \frac{V_{S0} - (1-m)E_{dc}}{Z_S}\sin\omega_S t \tag{19}$$

$$v_{cvs} = [V_{S0} - (1-m)E_{dc}]\cos\omega_S t + (1-m)E_{dc} \tag{20}$$

It is noted that the resonant characteristic impedance $Z_S = \sqrt{\frac{l_{vs}}{C_{vs}}} = \sqrt{\frac{l_{us}}{C_{us}}}$ and the resonant angular frequency $\omega_S = 1/\sqrt{l_{vs}C_{vs}} = 1/\sqrt{l_{us}C_{us}}$. For the voltages across the snubber capacitors to be completely discharged, the necessary condition is that the voltages of the two capacitors become less than zero at the real time t that satisfies $\omega_S t = \pi$. Thus, $v_{cvs}<0$ and the condition of $1-V_{S0}/2E_{dc}<m$ are obtained. In addition, the regenerating currents are not allowed to flow continuously. So, the condition of $m < 1$ has to be added. Finally, the conditions to determine the winding turns ratio of the auxiliary forward pulse transformers are rearranged as:

$$1 - V_{S0}/2E_{dc} < m < 1 \tag{21}$$

The value of V_{SO} selected in this paper is designed to be the smallest one.

It is also noted that the leakage inductances of the high frequency flyback transformer draw a constant value of the voltages across the auxiliary forward pulse transformer At_u and AT_v. This value is considered to be very small and does not have any disturbances to the functionality of the auxiliary transformers. However, at the zero-cross intersection of the output current, the triangular current flows through the primary side of the flyback transformer may have a very small peak due to the small rising time PWM gate signal that the voltage of the auxiliary pulse transformer may not be able to lead to the conduction of the diodes D_{us2} and D_{vs2}. This distorts the sinusoidal output current at the zero-cross time points. An adjustment in rising time PWM gate control signal at zero-cross time point in the experiment control circuit can be helpful.

4.4 Control signal processing implementation

Fig. 9 illustrates the control block diagram of the sinewave pulse modulated inverter circuit with the high-frequency flyback transformer link. This control block diagram displays the time pulse signals for both the isolated modified conventional hard-switching sinewave processing inverter with a flyback transformer link and the proposed isolated soft-switching sinewave processing inverter with the flyback transformer link. The modulation rate M is calculated by employing the reference output current I_{2orms} directly in the equation (12). The utility grid voltage e is detected for generating the sinusoidal voltage waveform signal $M \sin \omega t$ as a reference signal to be compared with the sawtooth carrier signal which is synchronized with the utility grid voltage e through PLL (Phase Locked Loop) circuit unit. Finally, the PWM signal is obtained as the gate pulse controlled switching signal and is directly used for turning on the DC-side active power switches in the proposed power regenerating snubber-assisted soft- switching sinewave processing inverter circuit with the high-frequency flyback transformer link. In case of the modified conventional hard-switching sinewave PWM inverter, the PWM signal will be divided into two channels and selected in accordance with the polarity of the grid voltage. Therefore, It is noted that the other low-frequency switching signal synchronized with utility voltage frequency for selecting the polarity of the output current in the AC side is also needed in addition to Fig. 9.

5. Performance Evaluations and Discussions

The design specifications and circuit parameters of the passive power regenerating snubber-assisted high-frequency flyback transformer linked sinewave pulse width modulation inverter using IGBT power modules is shown in Table 1.

Table 1. Design specifications of flyback transformer linked high-frequency inverter.

Source voltage in DC bus line	E_{dc}	200[V]
Power source voltage (rms)	e	100[V]
Power source commercial frequency	f_o	60[Hz]
Output power	P	1[kVA]
Carrier frequency of sawtooth waveform	f_s	16[kHz]
Low-pass filter inductance	L_f	300[μ H]
Low-pass filter capacitance	C_f	25[μ F]
Flyback transformer turns-ratio	n	0.785
Flyback transformer magnetizing inductance	L	126[μ H]
Snubber capacitance	C_S	0.06[μ F]
Resonant inductor	l_S	6.8[μ H]
Auxiliary transformer turns-ratio	m	0.67

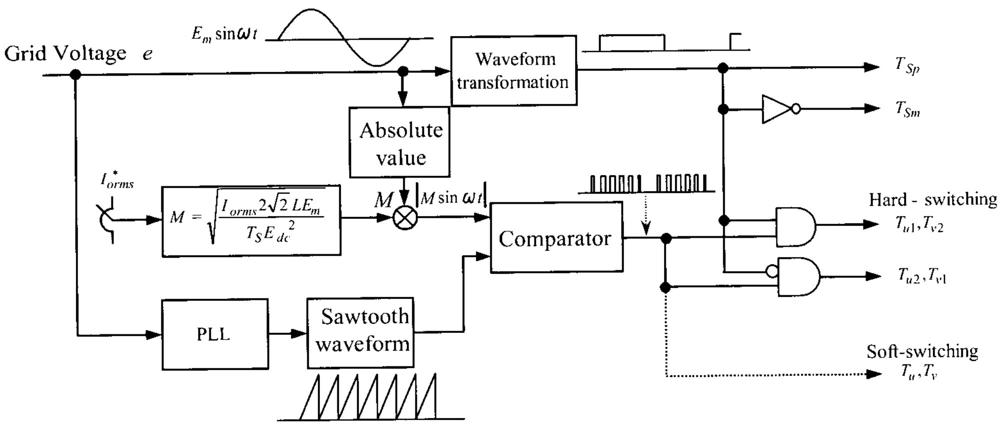
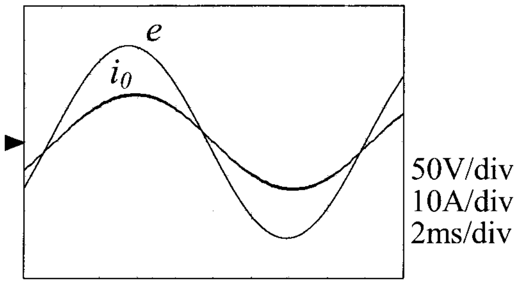
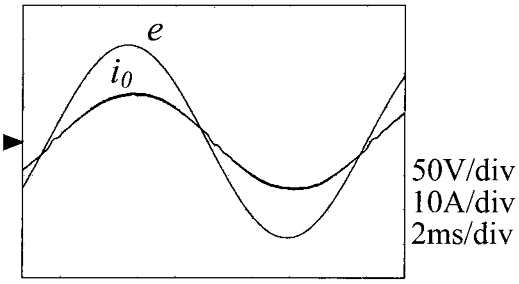


Fig. 9. Control block diagram of the sinewave inverter systems.



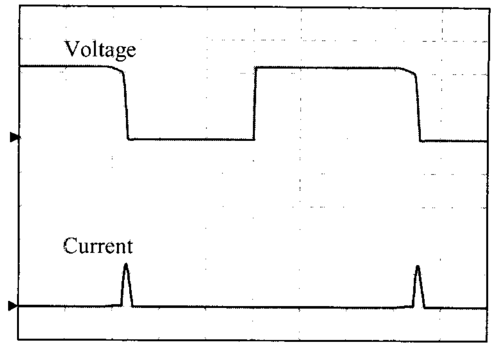
(a) Simulated hard-switching sinewave inverter



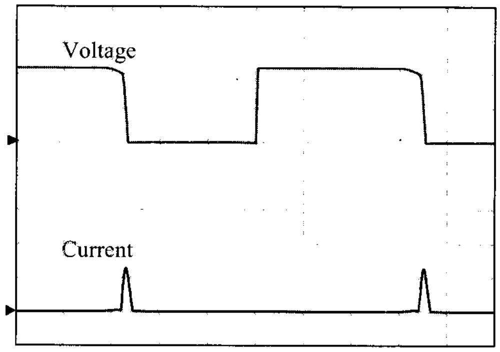
(b) Simulated soft-switching sinewave inverter

Fig. 10. The computer simulated voltage and current waveforms of the sinewave inverter.

The turns ratio of the high-frequency flyback transformer is designed for the capability of delivering the utility peak voltage with 10% deviation. Basing on the equation (12), the value of the flyback transformer magnetizing inductance L is designed according to the appropriate ranges of the modulation rate M and the commanded current I_{2orms}. The leakage inductance of the flyback transformer is small and negligible in this case. The power conditioning and processing conversion system is operated by the switching carrier frequency of 16kHz, which is designed for the small-scale 1kVA power conditioner for fuel cells in domestic equipment. On the basis of these designed parameters in Table 1, the computer simulations are conducted and the simulation results are respectively displayed in Fig. 10 and Fig. 11. The operating waveforms of the utility grid voltage e and the output current i_0 are represented in Fig. 10. Fig. 10 (a) displays the simulated operating waveforms in the case of the modified conventional hard-switching sinewave processing inverter circuit topology and Fig. 10 (b) displays the simulated operating waveforms in the case of the proposed soft-switching energy regenerative snubber circuit topology.



(a) Simulated voltage and current waveforms of the active power switches



(b) Simulated voltage and regenerating current waveforms of the snubber circuit

Fig. 11. The computer simulated switching waveforms of the soft-switching sinewave inverter (100V/div, 10A/div, 5 μ s/div).

The simulation results show that the sinusoidal output currents are in proportional and in phase with the utility grid voltage e. The comparative harmonic distortion factors (THD) of the modified conventional hard-switching sinewave PWM inverter and the proposed soft-switching sinewave PWM inverter are 2 % and 2.6 % respectively. The quality evaluations prove the effectiveness and the validity of the proposed power conditioning processing inverter for the utility interactive AC power system. Moreover, the power factors in the utility AC side of both inverters are as high as 0.995 despite of the effects of the filter capacitor C_f.

Fig. 11 represents the simulated operating voltage and current waveforms of the proposed soft-switching sinewave pulse modulation inverter system with the passive power regenerative snubber circuits when it is operated under the principle of soft-switching PWM control scheme. Fig. 11(a) shows the voltage and current waveforms of the DC-side power switches when the phase angle is about $\pi/2$. For every switching cycle, the voltages across two snubber capacitors in the feedback loop are completely discharged in a very short time at the beginning of the energy storage mode. The main active power switches are also turned off with the zero voltage soft-switching commutation.

It is noted that when the DC power switches are turned on, the DC side active power switch currents rise up from zero and are superposed by the regenerating currents simultaneously. However, the rising slopes are limited by the power regenerating inductors used here. Thus, it can be assumed that the DC-side active power switches are turned on under the condition of soft switching operation. Fig. 11(b) depicts the simulated waveforms of the snubber voltages and the simulated regenerating currents. It can be seen that when the power switches are actively turned on, the voltages across the snubber capacitors are discharged as the pulse regenerating currents flow.

6. Conclusions

In this paper, a new soft-switching sinewave pulse width modulation processing inverter with the high-frequency flyback transformer link for interfacing with the utility-grid power source was proposed and discussed for the new energy distributed power supplies such as the solar photovoltaic generation system, the fuel cell power generation system or any new type battery energy utilization system. Its operating principle was described and the evaluations of its performance were conducted on the basis of comparative study to the modified conventional isolated inverter with the high-frequency flyback transformer link. The state equations of both sinewave processing inverter circuits were introduced in order to establish the operating conditions for determining the circuit design parameters. By operating both sinewave inverter circuits under the condition of the discontinuous conduction mode, the turn-on zero current soft-switching operation could be achieved. Although the turn-off switching operations of the convention are conducted on the principle of hard switching, the newly proposed circuit topology with zero voltage soft-switching turn-off was introduced. By adding two regenerating energy snubber circuits, all the power active devices are operated on the basis of soft-switching operation. Also, the two regenerating energy snubber circuits could be operated passively. Therefore, no complex control scheme was required while the whole power conditioning system using sinewave processing inverter still remained reliable. On the basis of the computer-aid simulation, the steady state operation of the proposed sinewave power conditioning system with the benefit of soft-switching was validated. The distortion factor of the output voltage in this power processor was about 2.6 %, which is far below the required guideline of 5.0 % in the utility interactive power system. These facts proved the validation of the proposed inverter-type power conditioner. For the future work, the prototype using the proposed sinewave processing inverter circuits with the high-frequency flyback transformer link should be produced to consider the further improvement of the inverter efficiency and noise evaluations due to the ZVS soft-switching effectiveness for medium power utility interactive distributed power supply.

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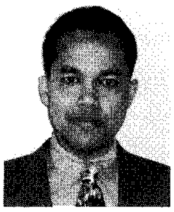

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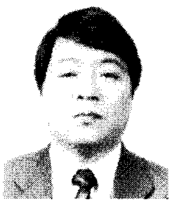

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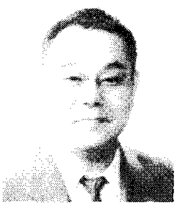

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