Utility-Interactive Modulated Sinewave Inverter with a High Frequency Flyback Transformer Link for Small-Scale Solar Photovoltaic Generator

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Abstract — This paper presents a novel prototype of the utility-interactive voltage source type sinewave pulse modulated power inverter using a high-frequency flyback transformer link. The proposed power conditioner circuit for the solar photovoltaic generation and small scale fuel cell has an isolation function due to the safety of the power processing system, which is more cost effective and acceptable for the small-scale distributed renewal energy conditioning and processing systems. The discontinuous current mode(DCM) of this power processing conversion circuit is applied to implement a simple circuit topology and pulse modulated control scheme. Its operation principle is described on the basis of simulation evaluations and theoretical considerations. The simulation results obtained herein prove that the proposed inverter outputs with sinusoidal waveforms and unity power factor currents are synchronized to the main voltage in utility power source grid. In this paper, the soft switching topology of high-frequency linked sinewave pulse modulation inverter is proposed and discussed.

Index Terms —High frequency link, Flyback transformer link, Sinewave modulated inverter, Utility interactive power processing, Solar photovoltaic power conditioner, Renewal conversion energy and sustainable energy, Soft-switching topology.

I. INTRODUCTION

IN recent years, it is commonly accepted to convert solar energy or fossil energy into the utility AC power with good quality by applying a variety of efficient power sinewave pulse modulated inverters with the latest MOS gate controlled power transistors and thyristors. Of these, in the applications of the solar phiotovoltaic(PV) energy, non-isolating type power conversion system using inverters become more and more popular because of system simplicity, low cost, high efficiency and compactness[1]. However, not only voltage and current matching but also the electrical isolation function between the inverter type power conditioner and utility interactive AC power source grid bus are both required for being implemented on the solar battery side. In particular, the PV system safety at present becomes an important issue for the residential applications in 100V or 200V AC power system. From an energy saving point of views, in this case, the electrical isolation function is practically required even though the high frequency isolating transformer linked inverter topology may become more complex[2].

This paper proposes a utility-interactive high-frequency transformer linked sinewave pulse inverter with its simple circuit configuration and pulse control for small scale distributed power applications. This new circuit topology treated here is composed of a high-frequency sinewave PWM inverter circuit with a flyback transformer link and contolled by the simplest discontinuous current control mode(DCM) scheme. The operation of this new power inverter circuit is presented on the basis of computer simulation, along with an example set of constructed variables and its evaluations. The soft-switching prototype of sinewave pulse modulated inverter with a high-frequency flyback transformer is presented in this paper.

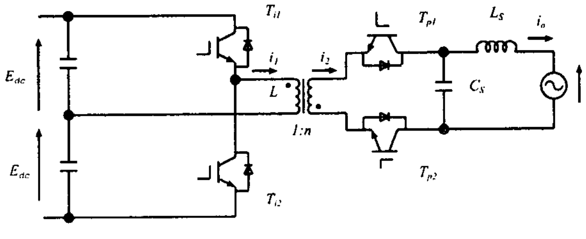


Fig. 1. Flyback transformer linked high-frequency inverter

II. CIRCUIT DESCRIPTION AND ITS OPERATION

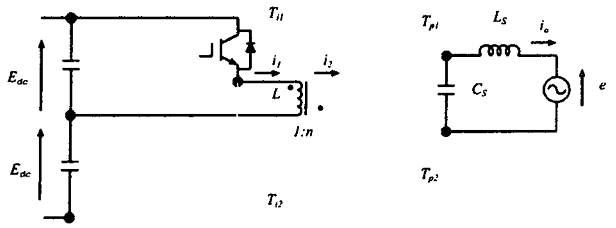
Fig. 1 shows the proposed utility-interactive high-frequency flyback transformer linked sinewave modulation inverter using the IGBT power modules. The flyback transformer in the sinewave inverter is operated by DCM and has the utility AC power source synchronized sinusoidal waveform with the output current. The PWM scheme processed for sinusoidal waveforms is controlled by the on and off mode for any of voltage source type half-bridge inverter power switches (T_{i1}, T_{i2}). In the first place, when either of the inverter switch is on, the energy from DC source due to the solar battery pannel is stored into the high-frequency flyback transformer and is released to the utility AC power side by turning off the same active power switch. The active power switches (T_{p1}, T_{p2}) in the utility AC power source grid side are selected to be able to synchronize and match the polarity of utility grid voltage e, which has the same operating frequency 50Hz or 60Hz as normal commercial power supply source. The low-pass filter (L_S, C_S) in the utility AC power side is inserted in order to smooth the discontinuous current with a high quality. The proposed single phase sinewave inverter circuit operation is described as follows, when utility side voltage is positive ($e > 0$).

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

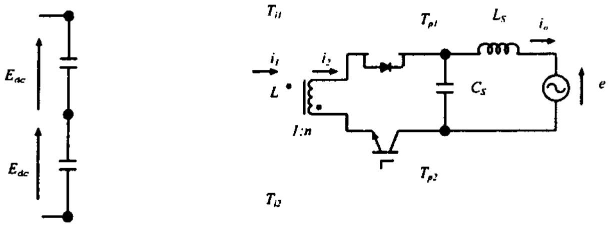
Fig. 2(a) illustrates the operating mode of this converter circuit when the active power switch T_{i1} is turned on while the polarity of the utility AC power system with voltage e is positive. To produce the same positive polarity for the output current, T_{p2} is already turned on in this mode. The diode of T_{p1} at the utility AC power side blocks the current and the magnetic energy is stored into the magnetizing inductor of the high-frequency flyback transformer.

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

Fig. 2(b) illustrates the operating mode of this power conver-



a. Operating mode when inverter switch is on



b. Operating mode when inverter switch is off

Fig. 2. Operating modes and equivalent circuits

sion circuit when the active power switch T_{i1} is turned off. The energy stored at the high-frequency flyback transformer is able to be released through the diode of T_{p1} and the IGBT T_{p2} into the utility AC power grid side. All energy will be completely released when this mode ends.

Similarly, in case when the polarity of the utility AC power system voltage is negative ($e < 0$), the inverter switch T_{i2} and the utility side switch T_{p1} is used for controlling operation mode.

Fig. 3 represents the relationship of the gate signals and currents in the primary and the secondary side of the flyback transformer. On-state signal (T_{on}) of the inverter-side active power switches (T_{i1}, T_{i2}) in the bridge arms is produced on the basis of comparison processing between a sawtooth waveform as a carrier signal and the sinusoidal signal ($M \sin \omega t$);M is the desired modulation rate and ω is the reference angle frequency, which is synchronous to the utility AC power system voltage. On the utility AC power side, on-state signal for the active power switches T_{p1} and T_{p2} in the secondary side of the flyback transformer is produced by referring to the signal of commercial power supply voltage, which is synchronized with the utility-grid system voltage e. Fig. 3(b) depicts the magnified current waveforms through the primary side and the secondary side of the flyback transformer. The current flowing through the secondary side of the flyback transformer is operated to become zero during the period T_S of saw tooth carrier signal. I_{2o} is the average value of i_2 during the period T_S and equivalent to the current that passes through the low-pass filter in the utility AC power side.

III. PRINCIPLE OF OPERATION

On the condition that the switching frequency of the implemented sawtooth carrier signal is high and system voltage ($e = E_m \sin \omega T_0$) is kept at the same level as the voltage of the filter capacitor C_S during one cycle of carrier signal. In the primary side of the flyback transformer, when the main active power switch is turned on, it can be derived as follows;

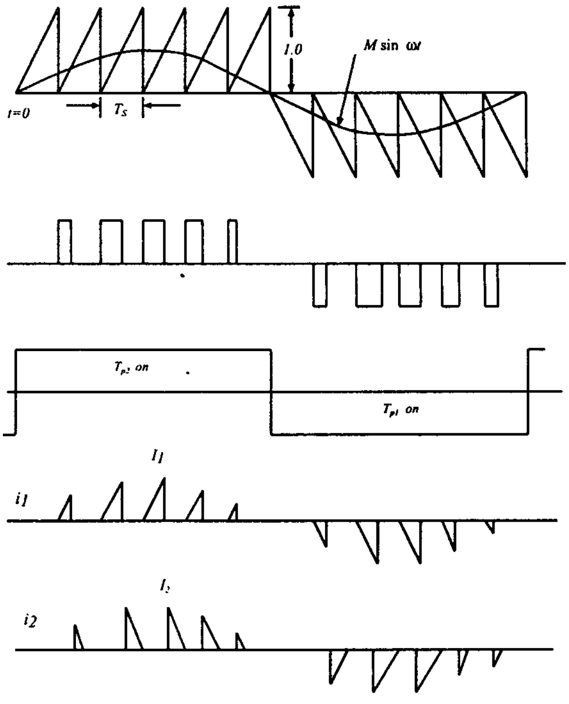
$$I_1 = T_{on} E_{dc} / L. \qquad (1)$$

On the condition that the utility AC power system voltage is constant during any operating cycle T_S, we can get,

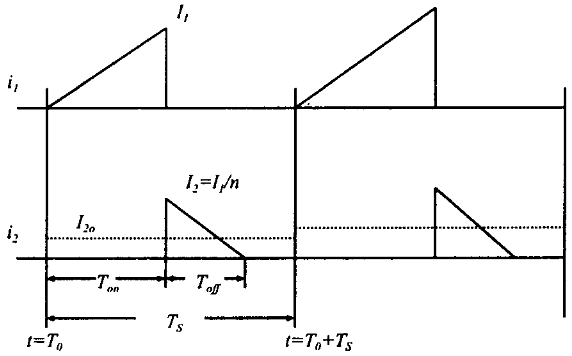
$$T_{on} = T_S M \sin \omega T_0. \qquad (2)$$

When the main active power switch is open in the primary side of the flyback transformer, the current of the transformer magnetizing inductance start to flow. Finally, in the secondary side, the current I_2 can be found as

$$I_2 = T_{off} E_m \sin \omega T_0 / n^2 L. \qquad (3)$$



a. Timing puls signals and sequences



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

Fig. 3. Control pulse sequences and current waveforms flowing through the input and output sides

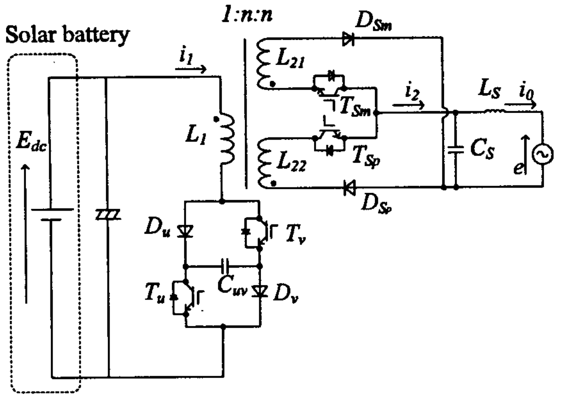


Fig. 4. Flyback transformer linked high-frequency soft-switching inverter

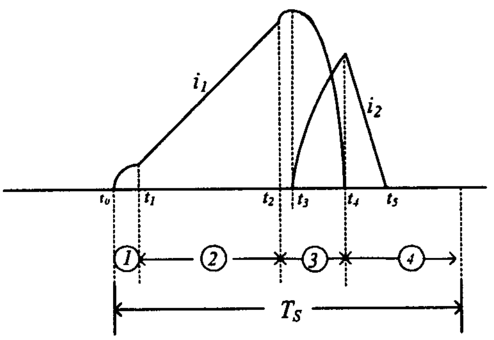


Fig. 5. Current waveforms flowing through the primary side and the secondary side of the flyback transformer in proposed soft-switching circuit

Since it is given that $I_2 = I_1/n$. We can get,

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

If the utility AC power system voltage in the power grid is a sinusoidal voltage waveform, the output current I_{2o} smoothed by the low-pass filter in the utility AC voltage side could be a sinusoidal current with the amplitude that is in proportion with M^2 when M is the modulation ratio. It is noted that the output current can be easily controlled by detecting the DC voltage E_{dc} and AC voltage amplitude E_m and adjusting the modulation rate by referring to the desired output current.

Moreover, under the DCM condition ($T_{on} + T_{off} < T_S$), the operating constraints is given under the conditions below;

$$M(1+nE_{dc}/E_m) < 1 \qquad \text{and} \qquad I_2/I_{20} > 2(1+E_m/nE_{dc}).$$

Then, on the condition that the energy is released to the utility AC power source side as shown in the mode of Fig. 2(b), $nE_{dc} > E_m$ is to be estimated. Therefore, the sinewave modulation ratio M is less than 0.5 in a usual operation.

IV. NEW SOFT-SWITCHING CIRCUIT TOPOLOGY

By employing a high frequency switching mode pulse control scheme on the operation of the active power switches in the primary side of the newly proposed inverter circuit, the power losses and electromagnetic noises can be more significant from an energy saving point of view. A soft-switching sinewave modulated inverter circuit topology applying two active power switch IGBTs in the primary side and two secondary windings with one IGBT each in the secondary side is also proposed here in Fig.4. A high-frequency pulse modulated inverter linked with two secondary windings of the flyback transformer, which is constructed similarly to the previously illustrated circuit, can be achieved along with the capability of soft-switching. The active power switches T_{Sm} and T_{Sp} are for selecting the polarity of the output current in the AC power utility side in accordance with the commercial grid AC voltage frequency. As well as the switch T_{p2} of the previously proposed inverter circuit, T_{Sp} is turned on when the positive half-cycle part of the output current waveform is to be achieved. On the other hand, T_{Sm} is turned on, the negative half-cycle part of the output current waveform is achieved. Each switch actively rotates according to the frequency of AC power electricity. The operation of the soft-switching based power conditioning and processing in the primary side can be explained as followings.

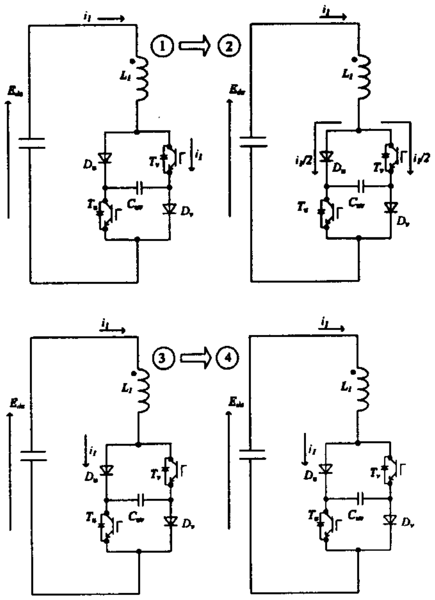


Fig. 6. Equivalent circuits of the primary circuit for each operation mode

In the first place, the capacitor C_{uv} is initially charged up to the same voltage level as E_{dc}. When the switch T_v and T_u are turned on at the same time to begin the operating mode ① at time t_0 as shown in Fig.5, a small resonant current i_1 flows through the active power switch T_v, T_u and C_{uv} (the loop of T_v - C_{uv} - T_u). In the second place, the capacitor C_{uv} is completely discharged very fast due to its small capacity. This triggers on the diodes D_u and D_v under the ZCS conditions at time t_1 to start the operating mode ②. After the diode D_u and D_v are respectively turned on, it is obvious that the current i_1 is divided into two parts flowing through both $D_u - T_u$ and T_v -D_v. During the operating mode ② which is defined by the interval between time point t_1 and t_2, the current i_1 of this operating mode ② maintains linearity until the active power switches T_v and T_u

are turned off with ZVS condition at the time t_2 to start the operating mode ③. Then, the resonant current i_1 starts to flow through C_{uv} to charge the capacitor by the same initial voltage E_{dc} as its starting. Finally, the diodes D_u and D_v are naturally turned off before the resonant current i_1 begins to reverse its direction at the time t_3.

The current i_2 starts to flow at the time t_3 during the operating mode ③ when the resonant current i_1 of the primary side flowing through L_1 starts to decline which results in the opposite sign of voltage across L_1. If T_{Sp} is already on(in case of positive output current), D_{Sp} conducts. Then, i_2 keeps rising until i_1 stops flowing at time ④ and transfers all energy through filter C_S and L_S. The sinusoidal waveform of i_0 is continuously generated and injected into the utility grid connection. Fig.5 illustrates the characteristics of the current waveforms of the primary side (i_1) and the secondary side (i_2) during one operating cycle of T_S. Fig. 6 demonstrates the equivalent circuits of each operation mode at the primary side of the flyback transformer at the operating time ①, ②, ③ and ④.

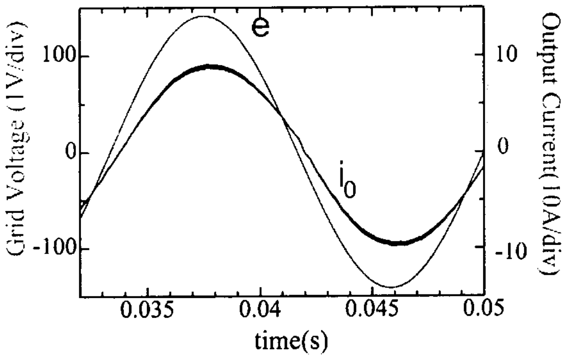


Fig. 7. Simulated voltage and current waveforms of the proposed inverter circuit in Fig.1

V. PERFORMANCE EVALUATIONS IN SIMULATION

Examples of the variables of the proposed utility-interactive flyback transformer linked inverter is represented below.

- DC power source : $2E_{dc} = 200V$, system network : 100Vrms, 60Hz
- power output : P=1 kVA, switching frequency : f_S=16 kHz
- winding ratio of flyback transformer : n=1.57, magnetizing inductance(estimated from the primary side of the flyback transformer) : L=31.6μH
- low-pass filter : L_S=300 μH, C_S=25 μF

Computing simulations of the proposed power inverter circuit in Fig.1 under the constants mentioned above is conducted. The sinusoidal pure waveforms of the utility AC system voltage e and output current i_o are illustrated in Fig.7. The simulated results prove that the output current waveform is injected to the utility AC power grid side in proportion to the utility grid system and is sinusoidal. The filtering capacitor C_S, which is used for smoothing discontinuous current, has an impact on advancing current phase but the power factor 0.995 could be acheived.

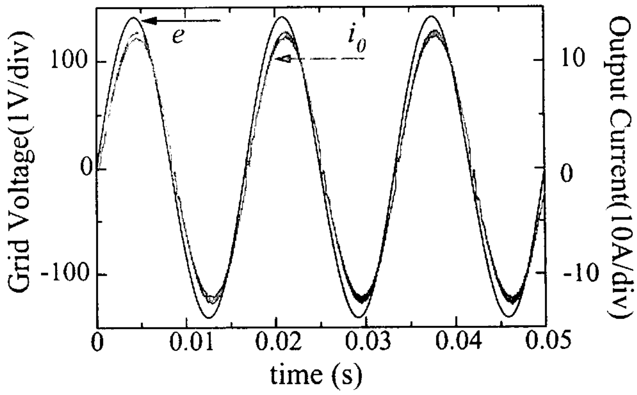


Fig. 8. Simulated voltage and current waveforms of the proposed soft-switching inverter circuit in Fig. 4

Fig.8 displays the simulated results of the proposed sinewave modulated inverter circuit in Fig.4 with the soft-switching function by comparing the utility AC system voltages e with the output current i_0. It is obvious that similar synchronized injection output current with higher amplitude can be gained by employing soft-switching high-frequency linked flyback transformer in the proposed inverter circuit. However, the small resonant current flowing through the capacitor C_{uv} always exists and becomes significant at point of near-zero output current. This is noted that more complex control scheme might be needed for achieving the sinusoidal waveform at the grid utility AC power side.

VI. CONCLUSIONS

This paper has presented a novel prototype of the utility-interactive inverter which is linked by the high-frequency flyback transformer operated under the discontinuous current mode. In addition to this, the operating principle of this sinewave modulated inverter has been described in details. Observing the circuit simulation analysis, sinusoidal output currents in the utility AC power source side was able to be acheived in principle.

In the future, the soft switching topology of the high frequency flyback transformer linked sinewave modulation inverter treated here should be studied for introducing the high performance power semiconductor switching devices such as High Conductivity IGBT(HiGT) and Carrier Storage Trench Gate IGBT(CSIGBT) and the trench gate power MOSFETs.

REFERENCES

[1] N. Kasa, T. Iida and H. Iwamoto, *Chopper-Type Inverter for Widely Used Small-Scale Applications of Solar Battery System*, Trans. of The IEE Japan, Vol.120-D, No.10, pp1237-1238, October 2000.

[2] H. Irie, S. Takashita, H. Kimura, M. Eguchi and K. Hiyoshi, *Applications of Emittance Transformer in Solar Energy Utility-Interactive Inverter*, Trans. of The IEE Japan, Vol.120-D, No.3, pp410-416, March 2000.

[3] Y.Konishi, S.Chandhaket and M.Nakaoka, *Utility-Interactive Flyback Transformer Linked Inverter for Renewal Energy System*, Proceedings of the 2001 Japan Industry Applications Society Conference, Vol.2, pp.739-740.

[4] M. Nagao, H. Horigawa and K. Harada, *Photovoltaic System Using Buck-Boost PWM Power Inverter*, Trans. of IEE Japan, Vol.114-D, No.9, pp885-892, 1994.