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High-Frequency Flyback Transformer Linked PWM Power Conditioner with An Active Switched Capacitor Snubber

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Abstract

A single active capacitor snubber-assisted soft-switching sinewave pulse modulation utility-interactive power conditioner with a three-winding flyback high frequency transformer link and a bidirectional active power switch in its secondary side has been proposed. With the aid of the switched-capacitor quasi-resonant snubber cell, the high frequency switching devices in the primary side of the proposed DC-to-AC sinewave power inverter can be turned-off with ZVS commutation. In addition to this, the proposed power conditioner in the DCM can effectively take the advantages of ZCS turn-on commutation. Its output port is connected directly to the utility AC power source grid. At the end, the prototype of the proposed HF-UPC is built and tested in experiment. Its power conversion conditioning and processing circuit with a high frequency flyback transformer link is verified and the output sinewave current is qualified in accordance with the power quality guidelines of the utility AC interactive power systems.

Key Words : Utility-AC-Connected Sinewave Power Inverter, High-Frequency Flyback Transformer, Discontinuous Conduction Mode(DCM)

1. Introduction

Many kinds of the renewable and sustainable energy related power supplies such as solar photovoltaic power generators, wind turbine coupled AC generators with a rectifier power stage, fuel cell power generators, thermoelectric device generators, new type batteries and super-capacitor banks used for the residential power utilization areas have begun to become commercially and economically practical[1]. Of these, sinewave power processing conditioners required to convert these alternative new energy related DC voltage sources into AC power have begun to be commonly used for the distributed AC utility connected system as well as for dispersed stand alone systems. Typically, utility AC power grids connected in parallel with residential loads or facility AC power loads are required to be electrically isolated from the unregulated alternative renewable DC voltage sources by

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means of a transformer for voltage boost matching, electromagnetic noise reduction and safety requirements[2].

For the sake of the voltage boost matching, noise reduction and the safety viewpoints. The ability to ground and isolate the busline of the utility AC power grid from the renewable power source supplies is one of the most important and practical considerations for designing and implementing the utility interfaced sinewave power conditioners. The electrical isolation links in power conditioner should be realized by inserting the transformer into the utility sinewave power conditioner[3-4]. Recently, instead of employing the bulky low frequency transformer at the utility AC grid connection, it is common to incorporate the high frequency transformer into the high frequency linked sinewave cyclo- converter, which is the main essential part of the power conditioner. However, the high frequency switching mode transitions in electric power decrease the actual efficiencies of the power conversion process in the power conditioning system. The efforts to reduce the high frequency switching power losses in the high frequency transformer linked utility AC connected power conditioner have been made so far. Most of the ideas are to implement the quasi resonant circuit components into the primary side of the high frequency transformer in the power conditioner in order to achieve the soft switching commutation[5]. Adding the auxiliary active resonant circuit components into the hard switching power conversion circuit topologies of the high frequency forward type transformer linked power conditioner results in the complication of the circuit configurations and control methods since the relationships of the gate voltage pulse width and the output currents can be highly nonlinear.

Thus, the complex power conversion circuit and system topologies of the general forward pass type transformer linked switch mode power conditioners are always difficult to implement and achieve the soft switching commutation for turn-on and turn-off transition operations[6]. On the other hand, the one switch or two switch type high frequency flyback transformer linked power conditioner is alternatively investigated as the sinewave PWM controlled utility AC interactive power conditioner[1-8]. However, more technological investigations to improve the power conversion efficiency have not been considered yet.

2. High Frequency Flyback Transformer Linked Utility Connected Power Conditioner

The conventional utility AC connected sinewave power conditioner isolated by high frequency flyback transformer is displayed in Fig. 1. The IGBT switches S_1 and S_4 in this circuit are turned on simultaneously by the high frequency sinewave PWM pulse series so that the positive discontinuous current i_1 is allowed to flow through the flyback transformer. When S_1 and S_4 are both turned off, the secondary-side current i_2 suddenly flows through the switch S_p and the AC low-pass filter (L_f, C_f) generating the positive part of sinewave output current i_0.

On the other hand, the switches S_3 and S_2 are similarly turned on in order to produce the negative part of sinewave output current i_0. In this case, the switch S_m is on so that the current i_2 can flow in negative direction. The sinewave output current i_0 is finally injected into the utility AC grid voltage to complete the power delivering processes.

The control pulse signals and the current operating waveforms are illustrated in Fig. 2. For simplicity, the high frequency saw-tooth carrier waveform is chosen instead of the triangular carrier waveform.

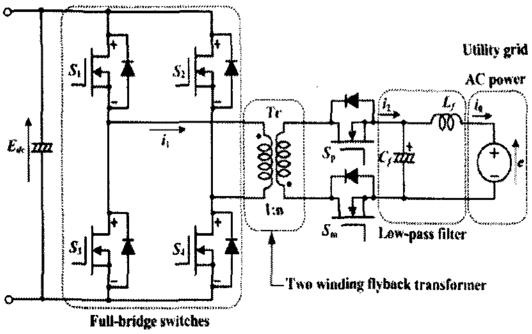

Fig. 1. High frequency flyback transformer linked utility connected inverter

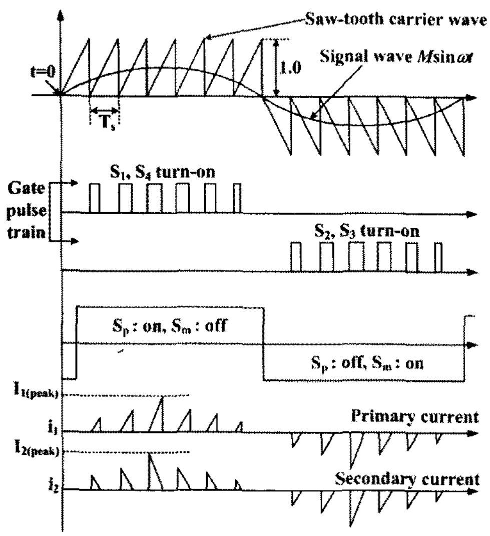

Fig. 2. Control diagram of inverter

It is compared with the sinewave signal synchronous to the utility AC voltage in order to generate the utility synchronous sinewave PWM trains can be for the primary side main switches. The pulse trains can be divided into two signals for both positive and negative switch selections. In general, the operating of the power conditioner with the high frequency flyback transformer link to isolate the inverter from the utility AC grid connection is to reduce the actual efficiency of the sinewave power conversion with a high-frequency link. It is necessary to simplify the transformer primary-side circuit configuration before adding the snubber circuit to assist the switching operation with less power losses and spike surges.

3. Switched Capacitor Soft Switching High Frequency Linked Power Conditioner

3.1 Circuit configuration

One of the simple methods to rearrange the transformer primary-side circuit configuration is to allow the transformer primary-side current i_1 to flow in only one direction so that two secondary -side transformer windings are constructed. Therefore, there are two circuit loops at the transformer secondary side for positive and negative direction of i_2 which is controlled by switch S_p and switch S_m, respectively.

The transformer primary-side circuit configuration becomes simpler. In addition, the auxiliary active switched capacitor snubber circuit can be implemented for the purpose of soft switching commutation. In this paper, a high frequency linked utility AC grid connected soft switching power conditioner with the lossless quasi resonant switched capacitor snubber capacitor is proposed and depicted in Fig. 3. The newly proposed power conditioner is composed by a single lossless quasi resonant switched capacitor cell at the primary -side of the three winding transformer.

This switched capacitor cell is the combination of two IGBT switches (S_1, S_2), two fast recovery diodes (D_1, D_2) and one lossless snubber capacitor (C_s). At the transformer secondary sides, the positive circuit loop (S_p, D_p) and the negative circuit loop (S_m, D_m) allow the transformer secondary-side current i_2 to flow in positive and negative directions respectively into the low-pass filter (L_f, C_f).

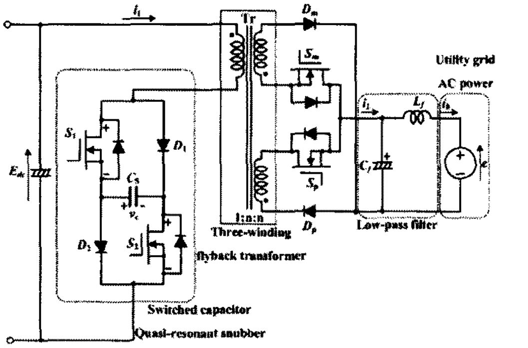

Fig. 3. Proposed soft switching sinewave switched capacitor snubber assisted inverter with a high frequency flyback transformer

3.2 Operating principles and Control method

The steady-state operations of the proposed utility AC grid connected power converter with a high frequency flyback transformer link can be roughly divided into two main operating modes. In the conventional power conditioner illustrated in Fig. 1, the transformer primary-side current i_1 increases linearly. Its secondary-side current i_2 decreases linearly. The overlapping time of current i_1 and i_2 due to the leakage inductance of the flyback transformer is so small that it can also be ignored. However, the primary-side current i_1 of the proposed soft switching power conditioner includes some resonant period due to the quasi resonant operation of the lossless switched capacitor snubber circuit. The overlapping period of current i_1 and i_2 has to be accounted into the circuit design. The transformer primary-side current i_1 and secondary-side current i_2 in one switching period T_S is illustrated in Fig. 4.

Furthermore, the switching period T_S is divided into 5 sub-operating modes denoted by submode 1 to 5. The equivalent circuit corresponding to each submode is illustrated in Fig. 5 with the details described below on the assumption that the utility AC voltage e is positive (e > 0).

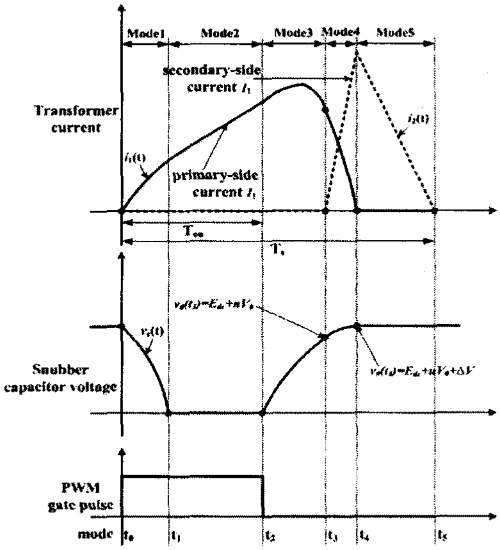

Fig. 4. Primary/secondary currents of flyback transformer and voltage with each operating mode

To investigate the total amount of the voltages charged into the lossless switched capacitor snubber by the turn-off transition operations during mode 3 and mode 4, the state equations are derived as described below.

$$E_{dc} = L_1 \frac{d}{dt} i_1 + L_e \frac{d}{dt}\left(i_1 + \frac{i_2}{n}\right) + v_c(t) \qquad (1)$$

$$V_0 = -nL_2 \frac{d}{dt}\left(\frac{i_2}{n}\right) - \frac{L_e}{n}\frac{d}{dt}\left(i_1 + \frac{i_2}{n}\right) \qquad (2)$$

For simplicity, the initial values of transformer primary-side current i_1 or $i_1(t_3)$ during mode 4 are denoted by i_1. The initial voltage v_c or $v_c(t_3)$ across the lossless switched capacitor during mode 4 are derived as $v_c(t_3) = E_{dc}+nV_0$.

By using both initial values of flyback transformer primary-side current and voltage across the lossless switched capacitor to solve eq.(1) and eq.(2), the additional voltage ΔV added to the DC input voltage E_{dc} found as

$$\Delta V = \frac{nL_e V_0}{n^2 L_2 + L_e}\left(1 - \cos\left(\tan^{-1}\frac{I_1}{K_0 \omega_r}\right)\right) \qquad (3)$$

Where,

$$\omega_r = 1 / \sqrt{c\left(L_1 + L_e - \frac{L_e^2}{n^2 L_2 + L_e}\right)},$$

$$K_0 = -\frac{nL_e V_0 C}{n^2 L_2 + L_e} + nCV_0$$

Furthermore, the maximum value of the additional voltage charged in the lossless switched capacitor snubber is simply estimated by

$$\Delta V < \frac{nL_e V_0}{n^2 L_2 + L_e} \qquad (4)$$

When the transformer primary-side switches S_1 and S_2 are simultaneously turned on by the sinewave high frequency PWM gate signal pattern, the primary-side winding of the flyback transformer is clamped by the voltage across the switched capacitor including the additional voltage ΔV.

Therefore, by calculating the additional voltage ΔV using eq.(4), the main flyback transformer can be appropriately designed for the utility AC connected power conditioner with a high frequency flyback transformer. By referring to the explanations of mode 4 in each switching period TS, in short period of the beginning time, the primary-side current i_1 increases resonantly resulting in the non-linear relationship of the PWM pulse width and the primary-side current i_1.

To generate the sinusoidal output current i_0, the primary-side current i_1 has to be controlled so as the peak current i_1 stay on the sinewave line. In Fig. 6, the control method of the proposed AC utility connected power conditioner is illustrated.

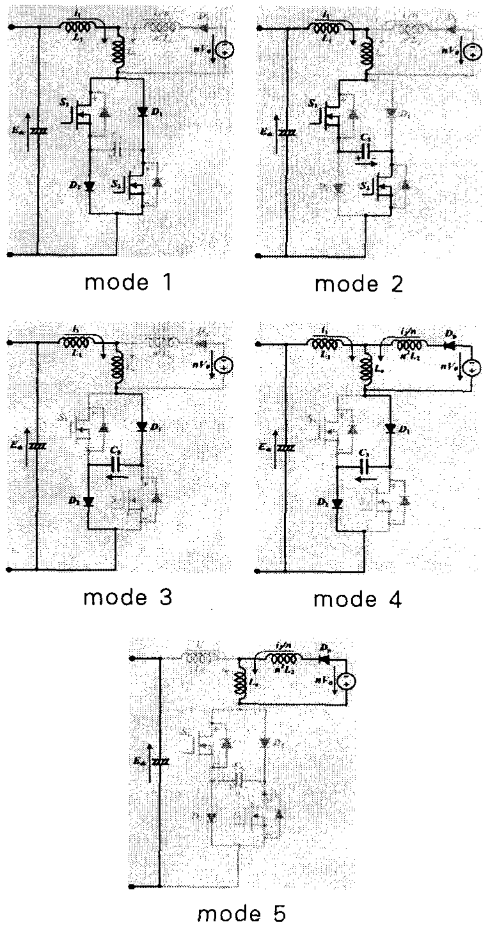

Fig. 5. Operating modes and their equivalent circuits

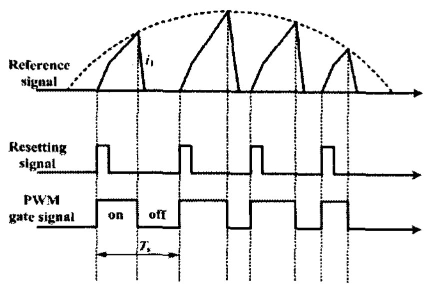

Fig. 6. PWM switching signal processing

The primary-side current i_1 is detected by the current sensor and is fed back to be compared to the AC utility synchronous reference signal. A high frequency small pulse signal produced by

PLL control circuit is used to reset the high frequency PWM gate signal for every switching period T_S.

When the detected current waveform increases to reach the sinewave curve of the reference signal, the high-level PWM pulse is brought suddenly to the low level so that the switches S_1 and S_2 are turned off. As a result, the primary peak current i_1 is controlled so that it does not become higher than the sinewave referenced signal. Since, the primary peak current i_1 is related directly to the secondary peak current i_2, the peak current i_2 and output current i_0 are also in sinusoidal shape.

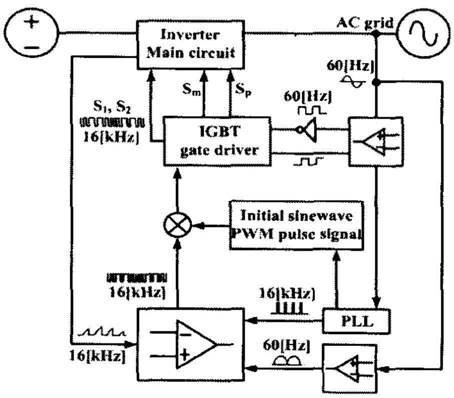

Fig. 7. Configuration of control circuit

Fig. 7 displays the gate signal processing diagram of the proposed control method for the proposed AC utility connected power conditioner. The absolute value of an AC utility synchronous sinewave reference signal, the small signal of primary-sine current i_1 and a 16[kHz]resetting pulse signal generated by PLL circuit are processed by a comparator to produce the high frequency PWM gate signal for switches S_1 and S_2.

However, at the start-up of the proposed power conditioner, the detected signal of current i_1 is so small that the generated PWM gate signal pulse is high for the longer time than the switching period T_S. Therefore, it is necessary to supply the off-line initial sinewave PWM gate signal at the start-up of the power conditioner until the primary-side current i_1 becomes high enough. After that, the on-line PWM gate signal fully takes place as the current-fed control gate signal.

4. Experimental Results and Their Evaluations

To prove the validity of the proposed AC utility connected power conditioner using the high frequency flyback transformer to achieve the electrical isolation, the experiments are conducted. The optimal design parameters are proposed as listed in Table 1.

Table 1. Design specifications and circuit parameters

Item	Unit	Value
DC voltage source	E_{dc}	200[V]
Utility AC voltage source (rms)	e	100[V]
Commercial AC voltage frequency	f_0	60[Hz]
Power output	P	1[kVA]
Frequency of carrier signal	f_S	16[kHz]
Low-pass filter inductance	L_f	300[uH]
Low-pass filter capacitance	C_f	25[uF]
Flyback transformer turns-ratio	n	0.87
Transformer magnetizing inductance	L	140[uH]
Switched capacitance	C_S	0.06[uF]

The experimental prototypes of the high frequency flyback transformer linked power conditioner shown in Fig. 1 and Fig. 3 were built and tested to verify the validity of the proposed high frequency flyback transformer linked power conditioner.

First, the modified type of hard switching flyback transformer linked power conditioner was implemented experimentally. Then, the energy regenerating passive snubber circuits were added to construct the proposed power conditioner with ZVS capability.

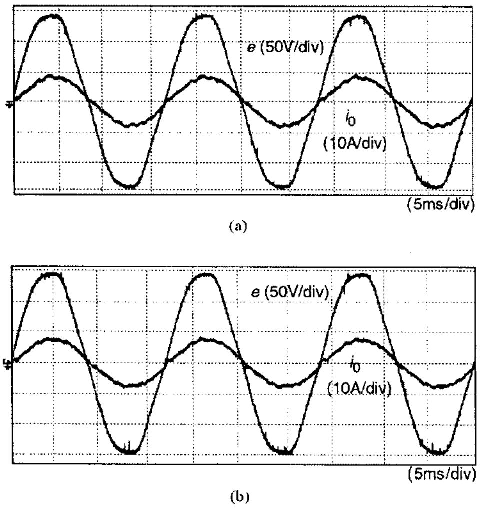

Fig. 8. Experimental output currents of power conditioner
(a) Conventional power conditioner
(b) Proposed power conditioner

The output currents injected into the utility AC grid line by the hard switching and the proposed soft switching power conditioner are shown in Figs. 8 (a) and (b), respectively. Both these Figures also depict the utility AC grid line voltage as the reference. Although the capacitor of the lowpass AC filter delays the current phases by absorbing the high frequency components, the power factors of both power conditioner are as high as 0.995 to 0.997.

Fig. 9 shows the measured primary-side current flowing through the main flyback transformer i_1, secondary-side current i_2, primary-side voltage waveform of the main flyback transformer and PWM gate signal.

As shown in Fig. 10, the regenerated resonant current flows through the primary-side of the three-winding auxiliary transformer, as seen at the beginning of the turn-on operation. However, it is very compared to the flyback primary-side current of i_1. Therefore, no significant effect appears on the operating principles. Fig. 10 also shows the waveform of the snubber capacitor voltage. The resonant current starts to flow when the voltage across the diode becomes zero at the beginning of the turn-on operation and returns to the DC source after half time of the resonant period, as seen in Fig. 11.

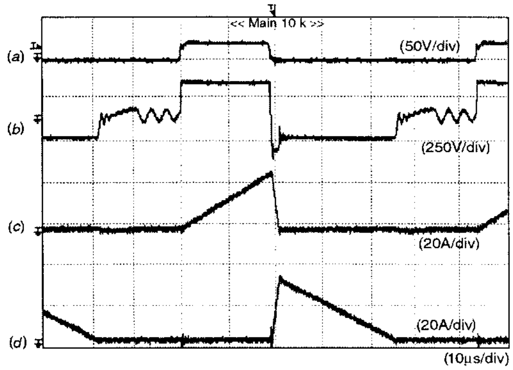

Fig. 9. Operating waveforms of proposed power conditioner
(a) PWM gate signal
(b) Flyback transformer primary-side voltage
(c) Primary-side current
(d) Secondary side current of flyback transformer

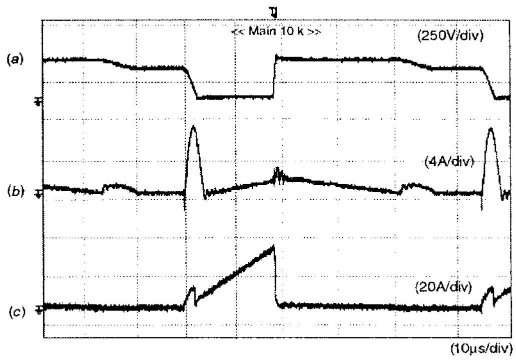

Fig. 10. Operating waveforms of proposed power conditioner
(a) Voltage across the lossless capacitor
(b) Current through the primary-side of the auxiliary transformer
(c) Primary-side switch current

It can be easily seen that the capacitor voltage is completely discharged very quickly within a few microseconds after the transformer primary power switches are turned on. Since the winding turns-ratio of the auxiliary transformer is high, when the snubber capacitors are discharged completely, the currents still flow through the high frequency resonant inductor for a while before being regenerated to the DC power source through diode and the anti-parallel diode of power switch.

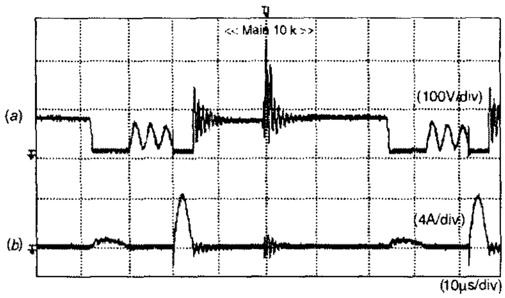

Fig. 11. Operating waveforms of proposed power conditioner
(a) Voltage across resonant loop diode
(b) Resonant current through the resonant inductor

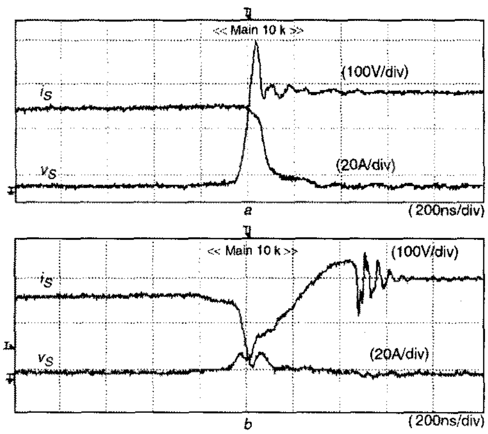

Fig. 12. Turn-off transitions voltage and current waveforms of primary-side active power switch
(a) Conventional power conditioner
(b) Proposed power conditioner

Therefore, the total current regeneration time is actually combined by the snubber capacitor voltage discharging time and the inductor current regenerating time. Fig. 12 (a) and (b) represent the primary-side switching voltage and current waveforms of the hard switching power conditioner and the proposed power conditioner, respectively.

From the Figure, it can be seen that the overlapping area of the voltage and current waveforms becomes smaller in the case of the proposed power conditioner, resulting in fewer power losses for high frequency switching. Fig. 13 displays a comparison of the conversion efficiencies measured on the modified hard switching power conditioner and the proposed power conditioner by the digital power-meter. The results show that the power conversion efficiencies averaged approximately 92.8[%] for the modified hard switching power conditioner and 93.1[%] for the proposed power conditioner.

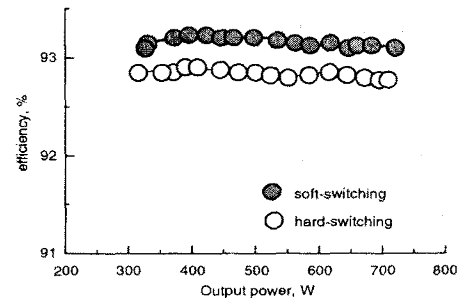

Fig. 13. Comparative actual power efficiencies of proposed ZVS and conventional power conditioner systems

The total harmonic distortion (THD) of the modified hard switching power conditioner averaged 3.8[%] and the soft switching power conditioner averaged 3.3[%]. The harmonic content for every order is below 5[%]. Although the energy regenerated resonant snubber circuits are added to the inverter circuit topology of the proposed power conditioner, the operating principles of the primary-side and the secondary-side current are not significantly affected owing to the similar THD values of the modified conventional and proposed power conditioner in the open-loop control scheme.

5. Conclusion

In this paper, two topologies of the flyback transformer linked high frequency utility AC connected power conditioners have been presented. In addition to the modification of a hard switching type utility AC connected power conditioner, the authors proposed a method to improve the power conversion efficiency by implementing the switched capacitor snubber unit in the primary side of the transformer to assist the ZVS turn-off operation.

The experimental results show the high conversion efficiency of the proposed flyback transformer utility AC connected power conditioner. The control method requires the addition of a current sensor inside the open loop. However, the algorithm is still simple and is able to generate the high quality of sinusoidal output current. The THD of the output current can be improved by introducing the close loop system. For the future work, the other types of snubber circuits are going to be investigated for improvement of the high frequency transformer linked utility AC connected power conditioner.

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