CYCLOCONVERTER-TYPE HIGH FREQUENCY LINK INVERTER FOR PHOTOVOLTAIC APPLICATION

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ABSTRACT

The abundance solar energy in this country has triggered the interest of researchers to develop local products to be used in the solar photovoltaic (PV) systems. Although the development of solar cell itself is somewhat far from target, the power converter design is well within reach. This paper presents a dc to ac power converter which can be suitably fitted in a solar PV system. The topology is an isolated cycloconverter-type high frequency link inverter that consists of three arms of bidirectional switches at the transformer secondary. The inverter has the advantages of light weight and reduced switch count. Furthermore, to overcome high voltage surge problem and power device switching loss, the natural commutation method that enables soft switching operation is applied. To verify the viability of the scheme, a low-power laboratory prototype is constructed. The prototype inverter is able to supply a near sinusoidal output voltage with a total harmonic distortion of less than 1%. The total power conversion efficiency reaches 86% when the output power is beyond 300W.

Keywords : *High Frequency Transformers, Inverters, Photovoltaic, Solar Energy*

1. INTRODUCTION

Recent sharp escalation in fossil fuel price has created a unique opportunity for renewable energy (RE) [1]. Solar energy in particular, has great potential to become the major RE source in this country. The worldwide market for solar photovoltaic (PV) system is expanding at an annual rate of over 30%, making it one of the fastest growing industries. Locally, the commissioning of PV systems has a double digit growth over the last five years. It is envisaged that the trend is likely to continue. The Solar 1000 project, the government-backed project to power a thousand homes with grid connected PV systems, is projected to take-off in 2006. This initiative is expected to be the impetus for a gear shift in solar research in this country. With the increasing awareness and concern over the pollution by fossil fuel, PV industry is looked upon as one of the main player in the energy sector of the future.

To harness the solar power, energy conversion technologies are required. A dc to ac converter, or popularly known as the inverter, is used to convert the dc power from solar into ac power. It is known that the inverter, which are mostly imported, comprise as much as 15% to 20% of the total system cost. Realising that most of the manufacturing facilities are readily available, it is natural that the inverter to be produced locally. However, it appears that the design and development of the inverter itself is lacking.

The inverter serves two purposes. First, it converts dc voltage (for example from PV panels) to a commercial ac voltage. Secondly, it should be able to provide (if required) electrical isolation between the load and source. Furthermore, inverters should be capable of bidirectional power flow to supply ac power for stand-alone or grid connected loads. The conventional voltage source inverter (VSI) with line frequency isolation transformer is commonly used to meet the abovementioned requirements. The typical set-up is shown in Figure 1. The inverter uses pulse width modulation (PWM) scheme to synthesise the output voltage close to a sine wave, which is then filtered by a low pass filter to obtain the fundamental voltage. The sinusoidal voltage is stepped-up/down and isolated from the load using the line frequency transformer.

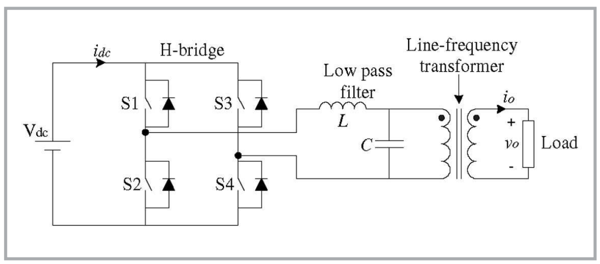

Figure 1: Conventional line frequency inverter

Although simple, the line frequency transformer is very bulky and expensive. Despite the high switching frequency of modern power switches, the transformer size remains large because its current is not alternating at high frequency. For compact PV system that can be fitted under a rooftop of a house, the bulky transformer is unsuitable. Recently, substantial work is carried out on the high frequency (HF) transformer link inverter topology as an alternative to the conventional inverter. Compared to the conventional inverter, the HF link inverter offers significant advantages in terms of compactness, weight and cost. This is primarily due to the small-sized HF transformer.

The two well-known HF link inverters are the "cycloconverter" and the "dc-ac converter" types. Both inverters are capable of bidirectional power flow. The cycloconverter HF link inverter is shown in Figure 2 [2]. The main advantage of this circuit is that it requires only two conversion stages, namely the HF square-wave bridge and the cycloconverter circuit. The major disadvantage is that all the (twelve) power switches operate at high frequency, resulting in appreciable switching losses. Furthermore, the required switching scheme for the switches in the cycloconverter section is quite complex.

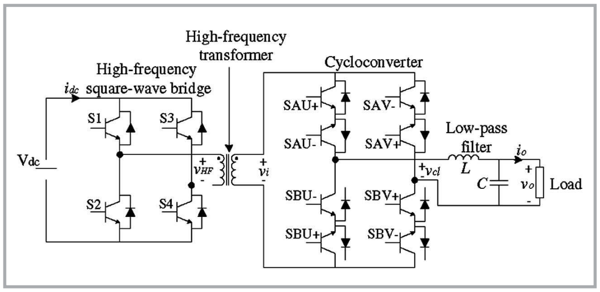

Figure 2: HF link inverter –" cycloconverter" type

The dc-dc converter type [3] consists of three power stages i.e. the HF PWM bridge, active rectifier and polarity-reversing bridge. The circuit configuration is shown in Figure 3. The main disadvantage of this topology is the substantial power losses occur due to the forward conduction losses of the active filter's diodes. Another drawback is that HF PWM bridge requires PWM modulated signal, which makes the transformer design less efficient.

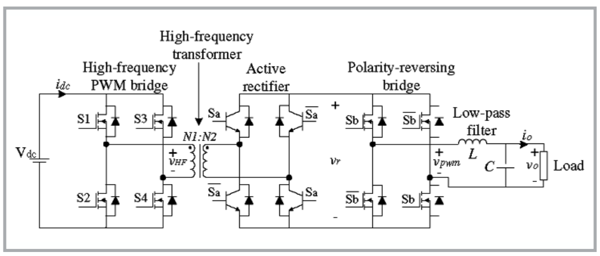

Figure 3: HF link inverter –" dc-dc converter" type

Regardless of the types used, the HF link inverter suffers from the problem of voltage surge at the transformer secondary. This results from the fast turning off of the secondary switches which leads to large transient energy released by the transformer leakage inductance. Dissipative snubbers are proved to be effective to solve this problem. However, the RC snubber network reduces the total efficiency. Active clamp circuits, which provide higher efficiency are also feasible but it leads to sophisticated circuit configuration and control method [4].

Another problem faced by HF link inverter is high transistor switching loss. This is due to hard-switching PWM that is imposed on the power switches. To reduce the losses, soft-switching method is proposed [5]. However, the implementation of this scheme is quite complicated. Other methods, such as regenerative snubber was also reported by [6]. This technique is able to simultaneously provide soft-switching operation as well as voltage surge reduction. From our literature review, the most promising solution employs natural commutation technique [7]. The problem of voltage surge is reduced without additional circuitry. Asymmetric control is applicable to this topology, which further improves the total efficiency. However this topology requires four bidirectional switches at the transformer secondary.

This work describes the design of a HF link inverter using a modified cycloconverter topology. The inverter consists of only three bidirectional switches at transformer secondary. Fewer switches imply the reduction in gate driver circuits and decreases in overall conduction losses. Simulation is performed to verify and analyse the proposed switching techniques. To prove the concept, a laboratory prototype is developed and typical results are discussed.

2. 2. THE PROPOSED TOPOLOGY

2.A. Power Circuit

The proposed power circuit consists of an H-bridge inverter, a centre-tapped HF transformer and a cycloconverter, as shown in Figure 4. The H-bridge inverter converts dc voltage into high frequency square wave voltage. When M1 and M2 are turned on, V_s appears across the transformer primary. When M3 and M4 are turned on, the transformer primary voltage is reversed to $-V_s$. The voltage waveform generated across transformer primary is symmetrical (50% duty cycle) and consists of only high frequency components. The low frequency (fundamental) component is absent. Therefore, the isolation transformer can be made small and light weight.

The cycloconverter on the transformer secondary converts the high frequency square wave into a low frequency sinusoidal PWM waveform. Effectively, it is a combination of controlled centre-tapped rectifier and a buck converter. "Powering" switches SX and SY rectify and regulate the voltage across transformer secondary while "freewheeling" switch SZ provides the freewheeling path. Each bidirectional switch consists of a pair of diodes and a pair of transistors and there is no connection between transistor drain- terminals. This configuration enables full control of current flow direction. Transistors group "+" are turned on when load current is positive while transistors group "–" are turned on when load current is negative. Transistors of the same bidirectional switch are never turned on at the same instant. Freewheeling switch is turned on alternately with powering switches.

The powering switches allow power flow between voltage source and the load. When switch SX is turned on, output voltage follows the transformer secondary voltage v_{21}. When switch SY is turned on, output voltage follows the transformer secondary voltage v_{22}. Note that throughout the following discussions, transformer secondary voltages are referred to, with transformer centre-tapped terminal as common node. By

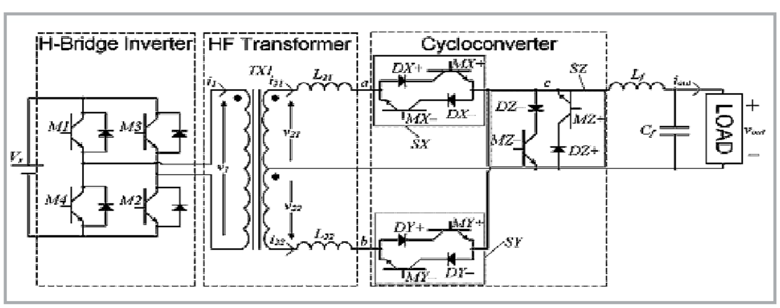

Figure 4: Proposed cycloconverter type HF link inverter

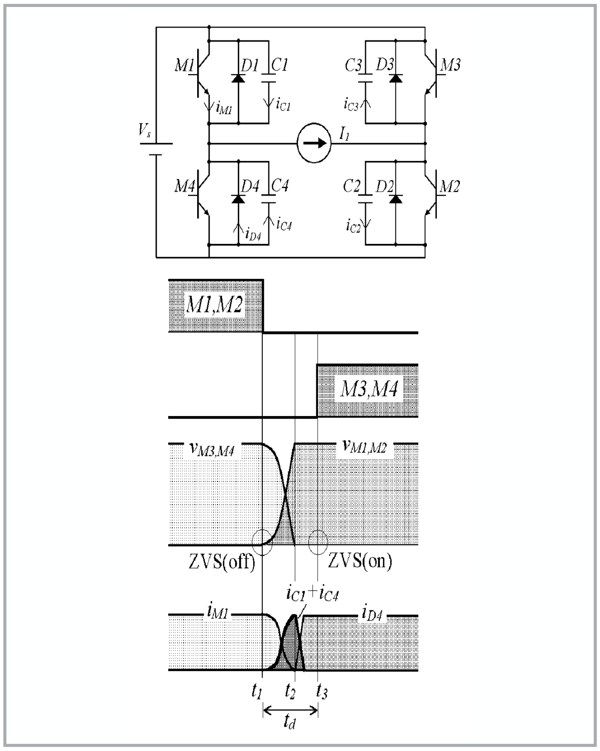

Figure 5: Forced commutation at inverter stage

controlling the duty cycle of powering switches, output voltage with various sinusoidal PWM pulse-widths can be generated. Both unipolar and bipolar sinusoidal PWM is feasible, depending upon the power flow direction.

The freewheeling switch SZ provides freewheeling path for load current when powering switches are turned off. The output voltage is drawn to zero. During freewheeling, no current flows through the powering switches, the transformer and the bridge inverter. Hence conduction loss is reduced. Using unipolar sinusoidal PWM control, longer freewheeling period can be achieved.

2.B.1. Forced commutation on the H-bridge

The simplified power circuit to illustrate the forced commutation on the H-bridge is shown in Figure 5. Capacitors *C1 – C4* represent the transistor output capacitances. The transistor leakage inductances are negligible in the analysis. Since overlapped switching technique is applied, transformer primary current I_1 lags the transformer primary voltage v_1. It can be assumed that transformer current remains constant throughout the transition period. In order to avoid current shoot-through fault, dead time t_d is provided between the turn-on time of incoming and outgoing transistors.

Initially, let both output voltage and current are positive. Transistors *M1* and *M2* are turned on and the current flows through these transistors. At time t_1, all transistors are turned off. Drain current of *M1* and *M2* is forced to zero, while *C1* and *C2* are charging; *C3* and *C4* are discharging. At t_2, output capacitances are fully charged and discharged, voltages of incoming transistors v_{M3} and v_{M4} drop to zero while voltages of outgoing transistors v_{M1} and v_{M2} rise to V_s. Transformer primary voltage v_1 is reversed. Anti-parallel diodes *D3* and *D4* are turned on and output current flows back to voltage source through these diodes. At t_3, transistors *M3* and *M4* turn on at zero voltage switching (ZVS) condition.

Consider only commutation at switching leg with transistors *M1* and *M4*,

$$i_{M1} + i_{D4} + i_{C1} + i_{C4} = I_1 \qquad (1)$$

When forced commutation process occurs, D4 is not conducting. Since I1 is constant,

$$\frac{di_{M1}}{dt} + \frac{di_{C1}}{dt} + \frac{di_{C4}}{dt} = 0 \qquad (2)$$

Assume all transistors are identical, and have equal output capacitance, $C1 = C2 = C3 = C4 = C_{out}$,

$$\frac{di_{M1}}{dt} = -\left(\frac{di_{C1}}{dt} + \frac{di_{C4}}{dt}\right)$$

$$= -2\,\frac{di_{Cout}}{dt} \qquad (3)$$

If it is assumed that the charging process is relatively linear,

$$i_{Cout} = C_{out}\,\frac{dv_{cout}}{dt}$$

$$= C_{out}\,\frac{\Delta v_{M3,\,m4}}{\Delta t}$$

$$= C_{out}\,\frac{V_s}{\Delta t} \qquad (4)$$

$$\text{where } \Delta t = 2 \text{ x } C_{out}\left(\frac{V_s}{t_2 - t_1}\right) + i_{M1} \qquad (5)$$

From Equation (3), it is clear that the mechanism of forced commutation is mainly determined by the transistor output capacitance, C_{out}. Equation (5) indicates that in order to operate the inverter transistors in ZVS condition, the load current i_{out} must be large enough to draw sufficient i_1. Also, the dead time between transistor turn on time must be longer than Δt to allow complete voltage transition. Output voltage transition from negative to positive is identical to as discussed, as long as the transformer current is lagging. Note that passive snubber capacitor can be connected in parallel with each transistor, to obtain a better control on the forced commutation process. Since the switching transition from M3, M4 to M1, M2 is identical to the abovementioned operation, all transistors in bridge inverter stage are also operating in ZVS condition.

2.B.2. Forced commutation at the cycloconverter stage

The cycloconverter stage circuit can be simplified to perform analysis on forced commutation, as shown in Figure 6. The transformer secondary voltage is assumed to be constant. It is modelled as a voltage source in series with an inductor that represents transformer leakage inductance. Since sinusoidal PWM control is applied, the load can be replaced with a constant current source, and output voltage is labelled as v_c. Furthermore, switches that remain turned off are assumed not participated in the operation. Since overlapped switching technique is applied, during switching transition between powering switch and freewheeling switch, transistor turn-on time overlaps.

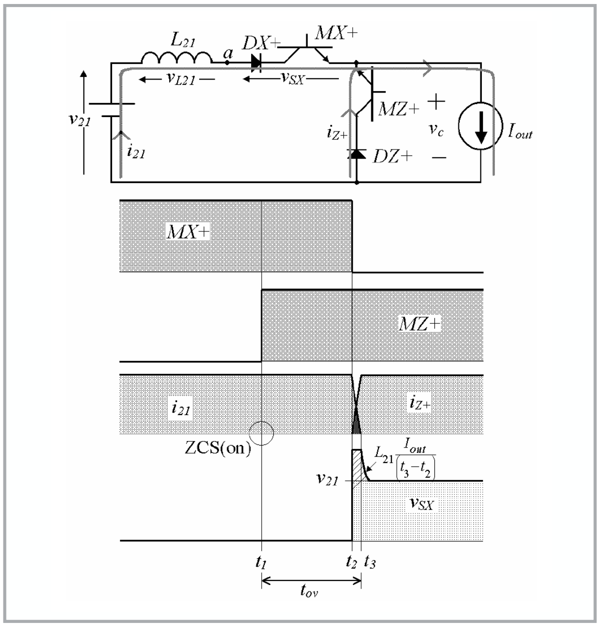

Figure 6: Forced commutation at cycloconverter stage

Assume input voltage and load current are positive and the incoming switch is Z. Prior to time t_1, *MX+* is turned on; power is transferred from the transformer to the load through this transistor. The load current is constant, so no voltage drop across the leakage inductance and v_c is equal to input voltage magnitude. When MZ+ turns on at time t_1, *DZ+* is reversed biased and it prevents commutation process. At t_2, MX+ is turned off and v_c is drawn to zero to allow the load current to forced commutate from *MX+* to *MZ+*. The commutation process ceases at t_3 when no more current flows through the transformer. The following equations show how the existence of leakage inductance causes voltage surge across SX:

$$v_{L21} = L_{21}\frac{di_{21}}{dt}$$

$$= -L_{21}\frac{I_{out}}{(t_3 - t_2)} \tag{6}$$

Apply Kirchjoff's Law to the path

$$v_{21} = v\,L_{21} + v_{SX} + v_c \tag{7}$$

Since v_c is drawn to zero, combine Equations (6) and (7) to get

$$v_{SX} = v_{21} + L_{21}\frac{I_{out}}{(t_3 - t_2)} \tag{8}$$

Equation (8) implies that during forced commutation period, energy stored in the leakage inductance is transferred to bidirectional switch *SX*. If the current transition time, i.e. $(t_3 - t_2)$ is small enough, it will generate sufficient voltage surge to damage the bidirectional switch. Also, note that MZ+ turns on at ZCS condition but *MX+* is hard switched. From the analysis performed, it shows that if both transformer secondary voltage and output current are of the same polarity, transition from freewheeling switch to powering switch will result in forced commutation. Even though overlapped turn-on time t_{ov} is provided between switching transition of transistor *MX+* and *MZ+*, natural commutation does not take place. The following discussions on natural commutation at cycloconverter stage will clarify the condition of forced and natural commutation.

2.B.3. Natural commutation at the cycloconverter stage

Figure 7 explains natural commutation at cycloconverter stage. The load is a current source, and output voltage is v_c. During switching transition between powering switch and freewheeling switch, transistor turn-on time overlaps to allow natural commutation mechanism.

Assume transformer voltage and output current are positive. Prior to time t_1, *MZ+* is turned on; output current freewheels through switch Z and the output voltage is kept to zero. There is no current flowing through transformer, transistor *MX+* and diode *DX+*. When *MX+* turns on at ZCS condition at time t_1, *DX+* is forward biased and the potential at point a is literally zero. Since output current is constant and the input voltage drops across the leakage inductance, current through *MZ+* is naturally commutated to switch *MX+* where the current ramps up. Applying Kirchhoff's Law to the circuit, the following equations are written:

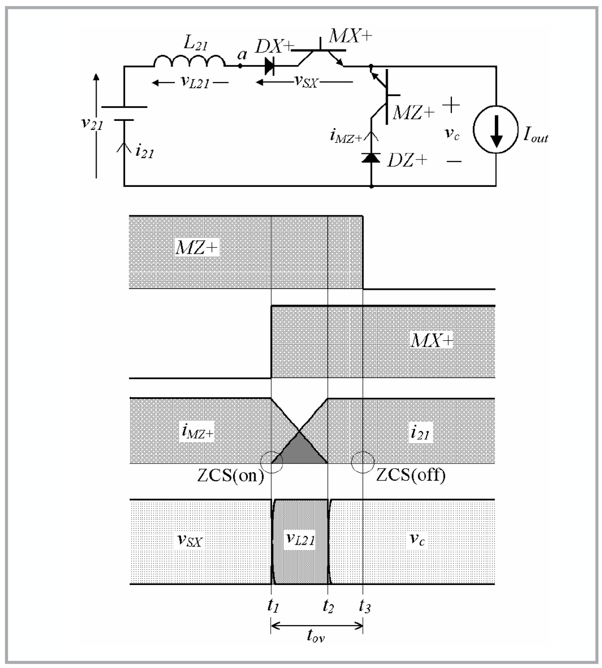

Figure 7: Natural commutation at cycloconverter stage

$$i_{21} + i_{MZ+} = I_{out} \tag{9}$$

$$\frac{di_{21}}{dt} + \frac{di_{MZ+}}{dt} = 0 \tag{10}$$

Since

$$v_{l21} = V_{21\text{-}peak} \tag{11}$$

and

$$v_{L21} = L_{21}\frac{di_{21}}{dt}$$

$$= -L_{21}\frac{I_{out}}{(t_2 - t_1)} \quad (12)$$

combining Equations (9), (10) and (11) yields

$$\frac{di_{21}}{dt} + \frac{di_{MZ+}}{dt} + \frac{V_{21\text{-}peak}}{L_{21}} = 0 \quad (13)$$

also,

$$\Delta t = t_2 - t_1$$

$$= \frac{L_{21} \times 1_{out}}{V_{21\text{-}peak}} \quad (14)$$

where Δt is the minimum overlap turn-on time required to complete natural commutation process. The commutation process ceases when current through *DZ+* reaches zero. At this instant, leakage inductance current becomes constant therefore it has no voltage drops. Therefore, input voltage drops across point c and *DZ+* is reverse biased.

From the analysis, it can be concluded that when the transformer is in powering mode (transformer secondary voltage, v_{21} or v_{22} is in same polarity with load current i_{out}), the process of storing energy in leakage inductance can be controlled using overlapped switching technique. Based on this judgment, it can be predicted that when the transformer is in regenerating mode (v_{21} or v_{22} is in different polarity from i_{out}), the process of releasing energy from the leakage inductance can also be controlled. To commutate from freewheeling switch to powering switch, transformer should be in powering mode. To commutate from powering switch to freewheeling switch, transformer should be in regenerating mode.

2.C. Switching Scheme

To operate the cycloconverter in natural commutation, a proper switching sequence needs to be applied. The chosen scheme is the edge-aligned unipolar PWM (EAUPWM) control, with its switching sequence shown in Table 1.

The EAUPWM switching pattern is illustrated in Figure 8. The output voltage is positively rectified at the first half, and negatively rectified at the second half. To change the output voltage polarity, the switching sequence of powering switches *X* and *Y* must be utilised. Only pulse-width *PW1* is required to control the powering switches. By using PWM technique, the magnitude of output voltage can be controlled. The transistors in freewheeling switch *Z* are turned on at all time because the diodes in freewheeling switch provide turn-on and turn-off operation. At the inverter stage, dead time t_d is added to every switching transition to avoid cross conduction. Overlap natural commutation period t_{ov} is set at switching transition from powering switch to freewheeling switch to allow soft-switching and voltage reduction operation. The typical operating waveform has 10 modes, where only modes 1 to 5 are explained below due to its periodical symmetry. Assume the initial input voltage and load current are positive.

- Mode 1 (Freewheeling period): During this period, *M1*, *M2, DZ+, MZ+* are in "on" state. The load current is shortened with this passage and completely separated from the dc source.
- Mode 2 (1st natural commutation period): *MX+* is turned on at ZCS condition to allow the current that flows through *MZ+* to commutate to *MX+*. When commutation process ceases, transformer secondary voltage drops at freewheeling switch and DZ+ is turned off.
- Mode 3 (Powering period): During this period *M1, M2, MX+* are in "on" state. The instantaneous power flows from dc source to the load.
- Mode 4 (Inverter dead time period): All four transistors of the inverter are in "off" state. Current flowing through the HF transformer remains constant because *DZ+* is still turned off. So the transformer current is forced commutated from *M1* and *M2* to *D3* and *D4*. Finally, *M3* and *M4* turn on at ZVS.
- Mode 5 (2nd natural commutation period): When the forced commutation process at inverter stage is completed, *DZ+* is turned on, load current begins to naturally commutate from *MX+* to *MZ+*. As the natural commutation process ceases, *MX+* turn on at ZCS condition.

3. RESULTS

To verify the concept that has been discussed, an experimental inverter is built. The inverter is rated at 750W. The prototype consists of two parts: power circuit and control signal generation circuits. The power circuits comprise of an H-bridge inverter, HF transformer, cycloconverter, snubbers and output filter. The control signals are generated using the Siemens MCB80167 fixed-point microcontroller. The filter inductor and HF transformer are wounded on the Ferroxcube ETD59 magnetic core. Figure 9 shows the output voltage and current of the inverter using the EAUPWM switching scheme. The output filter is chosen as L_f=1.6mH and C_f=2.2μF. The output voltage is 120Vrms, supplying a 32W resistor load. The switching frequency is set to 10kHz. There are small surges at zero crossings of the output voltage waveforms. This is because, without proper closed-loop control, the direction of the output current can only be estimated. Using the FFT function of the oscilloscope, the total harmonics distortion is measured to be about 0.76%.

The efficiency of the inverter is plotted in Figure 10. This is the overall efficiency, defined as the ratio of output power to input power. It is shown that the prototype is able to provide an overall efficiency of 84% when the output power is between 100W and 300W. When the power increases to more than 300W, the efficiency increases to approximately 86%. For comparison, the efficiency of the natural commutation phase angle topology that employs symmetric hard-switching and non-regenerative voltage clamp circuits, the overall efficiency is 72% [7].

The operating waveforms obtained from the experimental test rig are shown in Figure 11. The current flowing through transistor *M1*, $I_{C(M1)}$ surges from - 0.85A to +0.5A within mode 9 and 10. It can be suggested that the negative direction current surge is indeed current that flows through the anti-parallel diode. The current of transistor *M4* is forced commutated to the anti-parallel diode of transistor *M1* at mode 9. This forced commutation process results in ZVS operation at bridge inverter stage. When the commutation process has completed, the voltage across transformer secondary gradually increases. In the mean time, the RC snubber across the transformer secondary draws in current, which results in current surge (to +0.5A) at primary stage.

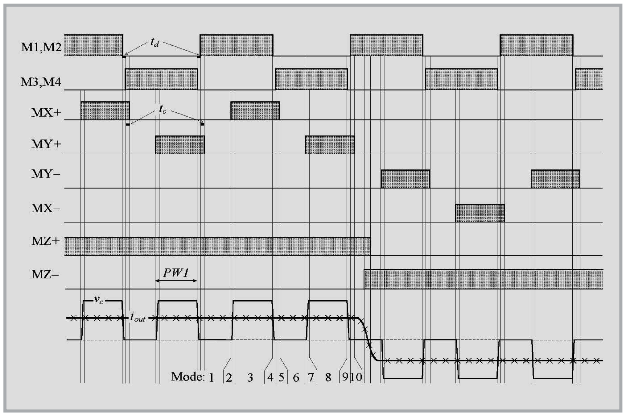

Figure 8: EAUPWM control signals

Table 1: Cycloconverter commutation process for different switching condition

Transformer secondary voltage	Iout	Incoming switch	Outgoing switch	Commutation
+v21	+	X	Z	Natural
+v21	+	Z	X	Forced
–v21	+	Z	X	Natural
–v21	+	X	Z	Forced
+v21	–	Z	X	Natural
+v21	–	X	Z	Forced
–v21	–	X	Z	Natural
–v21	–	Z	X	Forced
+v22	+	Y	Z	Natural
+v22	+	Z	Y	Forced
–v22	+	Z	Y	Natural
–v22	+	Y	Z	Forced
+v22	–	Z	Y	Natural
+v22	–	Y	Z	Forced
–v22	–	Y	Z	Natural
–v22	–	Z	Y	Forced

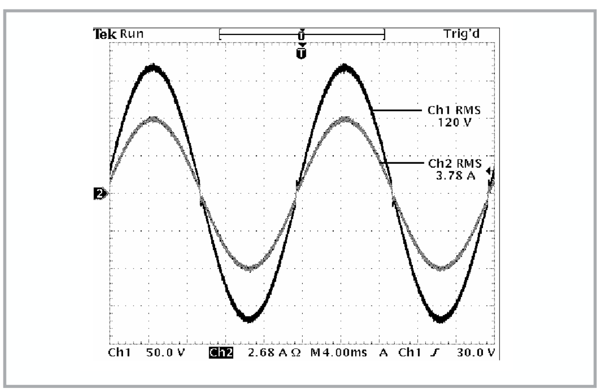

Figure 9: Output waveforms with resistive load

The diode reverse-recovery characteristics also effect the switching transition waveforms at mode 2,5,7 and 10. At the cycloconverter stage, and diodes are reversed biased when

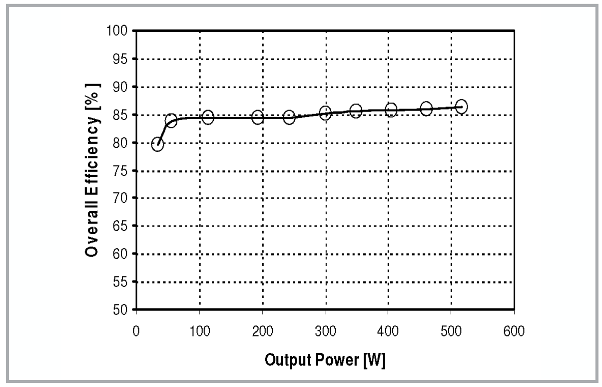

Figure 10: Overall efficiency versus output power

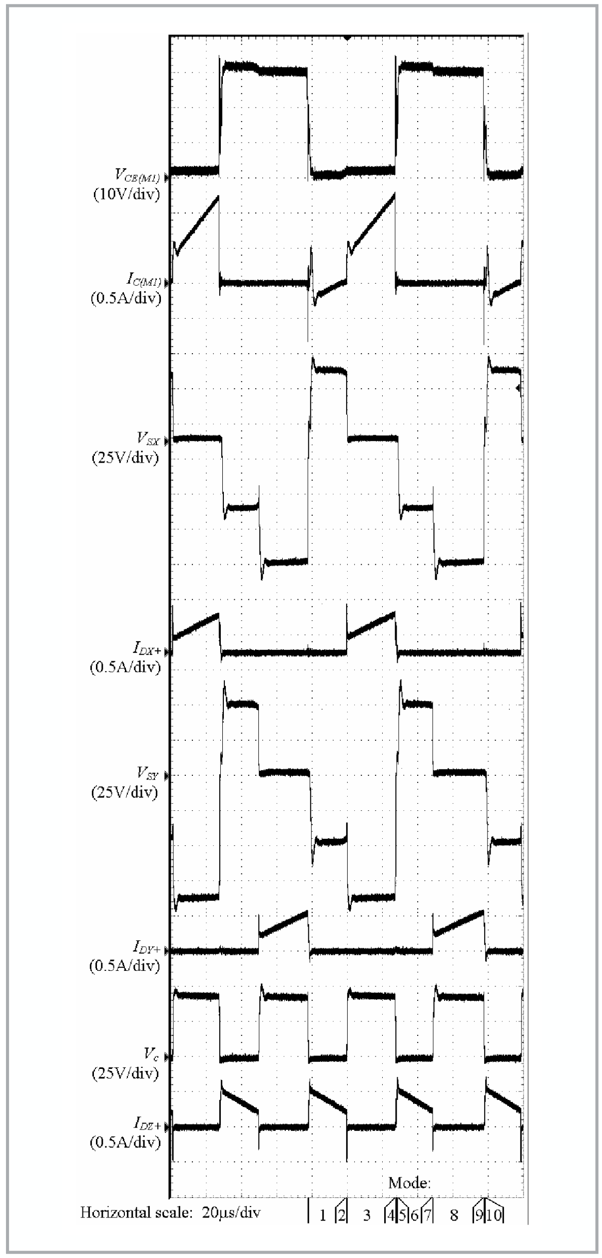

Figure 11: Experimental operating waveforms

natural commutation processes are completed. As a result, reverse-recovery current flows through the outgoing bidirectional switch while imposing positive current surge to the incoming bidirectional switch. The reverse-recovery current oscillates before settling to almost zero ampere, resulting in voltage overshoot across cycloconverter stage. The RC snubbers across transformer secondary reduce the oscillations in laboratory prototype and simulation circuit. Without the snubbers, idealised diode requires longer settling time, even though the magnitude of reverse-recovery current is relatively small.

Natural commutation technique is applied to reduce switching losses and voltage surge. It is not practical to experimentally show the effects on voltage surge due to the limitation of the device ratings. However, by investigating the operating waveforms during natural commutation period, the operation of voltage surge reduction can be verified.

The first natural commutation at cycloconverter stage is as shown in Figure 12. Between time t_1 and t_2, the voltage across the transformer secondary, v_a dips to less than half the magnitude of steady-state voltage. This is because within this period of time, voltage drops across the transformer leakage inductance to allow natural commutation from switch *SZ* to switch *SX*. Thus the voltage across the transformer secondary is controlled by natural commutation. The use of *RC* snubber across transformer secondary results in slow transition of voltage across bidirectional switch. Therefore, soft-switching operation of switch *SX* is not obvious at time t_1. Soft-switching operation of switch *SZ* can be observed during the turn-off instant.

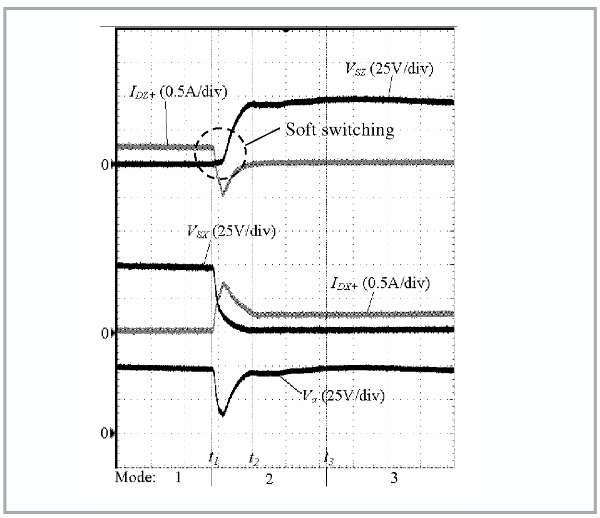

Figure 12: The first natural commutation at cycloconverter stage

The effects of diode reverse-recovery characteristics can also been observed in the waveforms of IDX+ and IDZ+. In addition, the voltage overshoot across switch SZ occurs after natural commutation has completed at time t2. This verifies that the voltage overshoot is due to the oscillation resulted from reversed-recovery current. The oscillation of reversed-recovery current that occurs after time t2 is not significant. However, it would result in significant oscillation to the voltage across the transformer leakage inductance. The RC snubber across transformer secondary reduces the oscillation in the prototype.

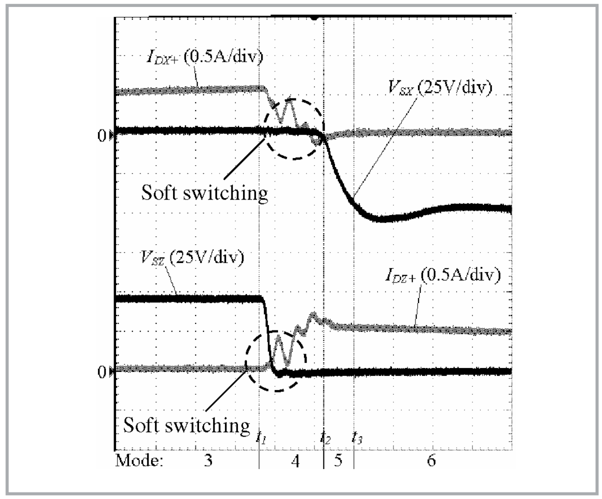

Figure 13: The second natural commutation at cycloconverter stage

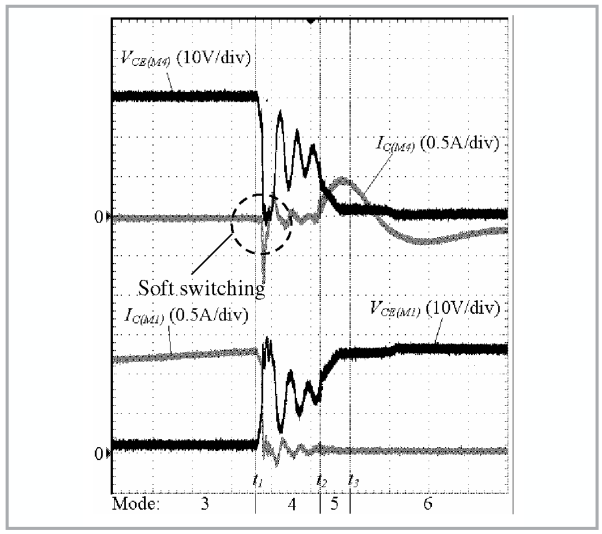

Figure 14: Forced commutation at bridge inverter stage

The second natural commutation in Figure 13 occurs when the voltage across transformer secondary is inverting from positive to negative. It is observed that the current waveforms during natural commutation are not as smooth as those shown in Figure 12. This is because voltage across the bidirectional switch SY is changing from negative to positive; so current is drawn in to turn off *MY*+ and turn on *DY*+. The current is required to charge and discharge the output capacitances of power devices. Nevertheless, soft-switching processes of both bidirectional switches are obvious at time t_1 and t_2. Similarly the voltage across switch *SX* overshoots after natural commutation process at time t_2.

Forced commutation in bridge inverter is as depicted in Figure 14. There are significant voltage oscillations across the transistors between time t_1 and t_2. This is mainly due to oscillating reverse-recovery current of switching operations of transistor M4 can be clearly observed at time t_1. The current of transistor M4-oscillates after t_2 because the current, which is drawn in to RC snubber, is mirrored to transformer primary. The RC snubber derives current to reduce the voltage oscillation across transformer secondary.

4. CONCLUSION

This paper describes an isolated cycloconverter type high frequency link inverter suitable for PV application. The main feature of the inverter is reduced switch count and lightweight. To overcome the voltage spike and high losses, the natural commutation method with overlapped time is applied. Furthermore, the edge-aligned unipolar PWM switching techniques is proposed to reduce the transistor conduction loss. To prove the concept, a 750W prototype inverter was built. The PWM generation is based on the Siemens 80C167 16-bit fixed-point microcontroller. The laboratory prototype is able to generate a near sinusoidal output voltage with total harmonic distortion of less than 1%. The power conversion efficiency is measured to be about 84- 86%. ■

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PROFILES

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