# An Improved 'DC-DC Type' High Frequency Transformer-Link Inverter by Employing Regenerative Snubber Circuit

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*Abstract*--This work proposes a bidirectional high frequency (HF) link inverter using center-tapped high frequency transformer. The main advantage of this topology is the reduced size of the converter. However the utilization of the high frequency transformer results in the occurrence of high voltage spike at its secondary. To solve this problem, we incorporate a regenerative snubber to clamp the spike and subsequently feed the energy back to the power circuit. The inverter also utilizes less number of switches, which results in lower conduction and switching losses. This paper describes some of the important aspects of the snubber design. It is verified with a 1kW inverter prototype.

*Index Terms*—High frequency link, inverter

## I. INTRODUCTION

The 'dc-dc converter type' high frequency link inverter was first described in [1]. Its basic power circuit is shown in Fig. 1. It consists of three power stages i.e. the HF PWM bridge, active rectifier and polarity-reversing bridge. The main advantage of this topology is the significant reduction in the transformer size. This is because the transformer is operated at high frequency.
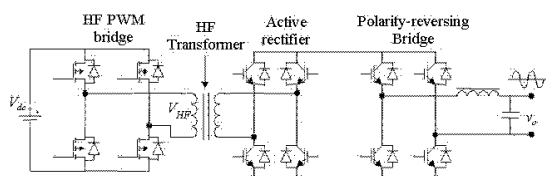


Fig. 1. The 'dc-dc converter type' high frequency link inverter.

In a previous paper [2], we have described a variation of this topology using the center-tapped transformer. We have shown that with this circuit, fewer switches are required compared to the topologies proposed in [1]. Using the center-tapped transformer however, has one major drawback; the voltage across the switch at the transformer secondary is doubled relative to the non-center tapped type. As the voltage stress across the switch is already high, additional voltage spike can make the power switch vulnerable. In this paper we proposed an improvement to our previous topology. We introduce a regenerative snubber network for the active rectifier that effectively reduces the spike to a very low value. In

addition, because of the lossless (in the ideal case) nature of the snubber, the energy contained in the voltage spike is pumped back to the main power circuit.

## II. INVERTER WITH REGENERATIVE SNUBBER

### A. Power Circuit

The proposed high frequency link inverter is shown in Fig. 2. The timing diagram for the key waveforms of the power stage is illustrated in Fig. 3. At the first stage, the high frequency PWM bridge converts the dc voltage to a 50Hz modulated sinusoidal PWM (SPWM) high frequency ac voltage. Then, this voltage is isolated and boosted using a center-tapped high frequency transformer. In the next stage, the high frequency SPWM waveform is rectified using a center-tapped active rectifier. The active rectifier, which consists of power switches and anti-parallel diodes, enables bidirectional power flow. For transfer of power from the source, the diodes are utilised. For reverse power flow, the power switches S3 and $\overline{S3}$ are turned-on. The rectified PWM waveform ($V_{HF\,rect}$) is then low-pass filtered to obtain the rectified fundamental component. Finally, using a polarity-reversing bridge, the second half of the rectified sinusoidal voltage waveform is unfolded at zero-crossing, and the sinusoidal output waveform is obtained. By using the center-tapped rectifier circuit, the number of bidirectional switches is reduced. Furthermore the polarity-reversing bridge utilises only supply switching frequency (50Hz) switches.
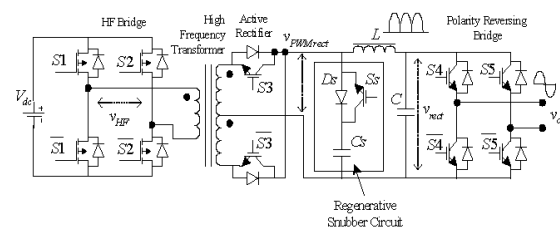


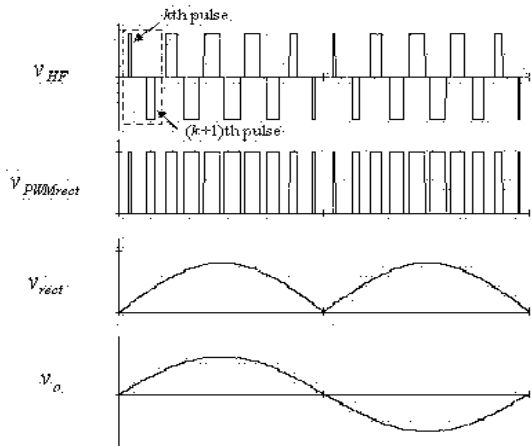Fig. 2. Block diagram of the proposed inverter.

Fig. 3. Key waveforms at different stages of the dc/ac conversion.

One of the main concerns of high frequency link inverter is the unavoidable presence of leakage inductance at the transformer secondary. The energy stored in the leakage inductor is one of the primary sources of voltage spike in the power transistor. The leakage inductance carries the same current as the transistor switch when the switch is on. When the current at the transistor is turned off very quickly, the rate of change of current, i.e. di/dt is very high, resulting in high voltage spikes to appear across the switches. If not properly controlled, the spikes may result in the destruction of the switches. The normal method to dampen the spike is to use an RCD snubber network across the switch, as illustrated in Fig. 4 [2]. However, the required snubber capacitor, $Cs$, for adequate spike suppression can be quite large. Consequently high discharge energy will be dissipated in snubber resistor, $Rs$, when the switch turns back on. This mandates for the use of high power $Rs$, which in many cases lead to further loss in the inverter's efficiency.

In this work, we introduce a regenerative snubber at the transformer's secondary circuit. Using this snubber, the spikes across the active rectifier switches are effectively reduced to a very low value. In addition, the

energy contained in the voltage spikes is injected back to the main power stage. This will further increase the efficiency of the inverter.
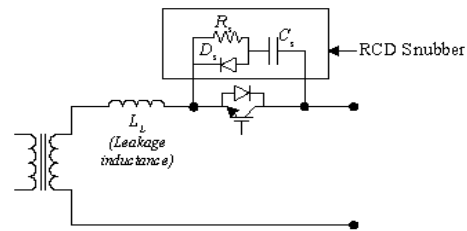


Fig. 4. RCD snubber

### B. Regenerative snubber network

Fig. 5 shows the regenerative snubber network. The associated timing diagram is shown in the same figure. This snubber circuit is used to reduce the voltage spike across the active rectifier's switches (S3 and $\overline{S3}$ ) to a safe level. From the timing diagram in Fig. 5, it can be seen that voltage spike occurs during switching transitions. Circuit shown in Fig. 6 details the snubbering operation during this transient moment. When the gate signal ($V_{PWM}$) is applied to any of the rectifier's switch, that switch will turn on and the adjacent switch will turn off. The energy stored in the leakage inductance of the transformer will appear as voltage spike on the adjacent switch. Assuming the snubber diode ($Ds$) and switch ($Ss$) are ideal, the voltage level across the capacitor ($Cs$) without spike is $v_1$. When spike occurs, $V_{HFrect}$ increases, causing the snubber diode $Ds$ to be forward biased and consequently charges the snubber capacitor $Cs$. The capacitor $Cs$ dampens the spike by reducing the di/dt. The charging process that takes place during $t_1$ to $t_2$ causes the capacitor voltage $v_{cs}$ to rise. When $v_{cs}$ equals $v_2$, i.e. when the capacitor voltage equals $v_{HFrect}$, the charging process stops. Snubber diode $Ds$ is reverse biased and $Cs$ starts to discharge its energy into the power circuit via $Ss$. The discharging continued until the end of the PWM pulse. When this point is reached, $Ss$ is turned off, and the discharging process stops. Voltage $vcs$ is maintained at its equilibrium level ($v_1$) until the next charging process occurs.
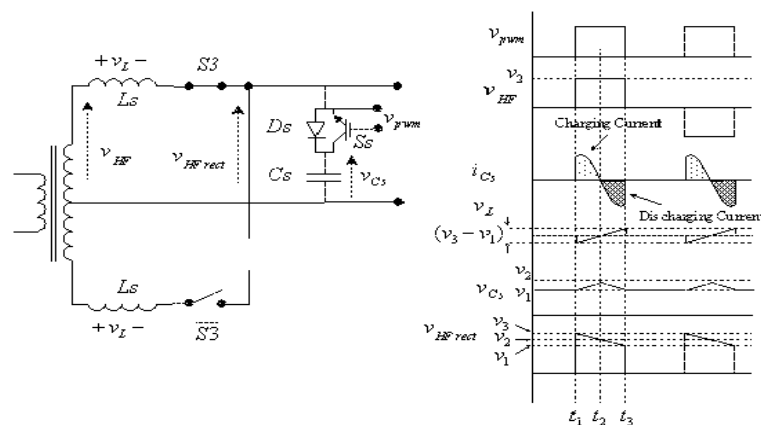


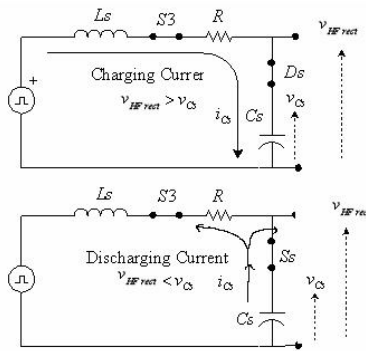Fig. 5. Circuit of regenerative snubber network and the associated timing diagram.

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Fig. 6. Equivalent circuit of the regenerative snubber network during snubbering operation.

## III. EXPERIMENTAL RESULT AND DISCUSSION

The HF bridge is constructed using the IRFP460 power MOSFET. It is a low $R_{ds(ON)}$ device with good switching capability. The active rectifier's switch is built using the IRG4PH40K IGBTs with discrete 20EFT10 fast recovery anti-parallel diodes. The rated voltage for the diode is 1200V, in precaution to the possible voltage surge that may result from the transformer leakage inductance. The polarity-reversing bridge is constructed using SK25GB065 IGBT module. Since almost all the surge voltages have been dampened before entering the polarity-reversing bridge, the chosen power switches are only rated at 600V. Using low voltage IGBT, the forward

conduction losses can be minimized. The specifications of the inverter are as follows:

- Input voltage ranged from 60V to 110V.
- Sinusoidal output voltage 220-250 Vrms, 50 Hz.
- Maximum output power of 1 kW.

The output voltage and current waveforms for resistive and inductive loads are shown in Figs.7 (a) and (b), respectively. The latter oscilogram indicates that the inverter is capable of carrying bidirectional power flow.

Fig. 9 shows the oscillograms that depicts the operation of the regenerative snubber. As can be seen, when the PWM pulse in applied to S3, at the transition point, the snubber capacitor charges and absorbs the transient energy. As a result, for the adjacent switch $\overline{S3}$, the spike is suppressed. The corresponding charging and discharging voltage at $C_s$ is also shown in this figure. The results are identical to the theoretical timing diagram in Fig. 5. Clearly there is a close agreement between the theoretical and practical results.

Fig. 10 shows the collector emitter voltage ($V_{ce}$) of switch S3 before and after insertion of the regenerative snubber. It can be seen that before the regenerative snubber is inserted, voltage overshoot of about 37% of the amplitude occurs. After the insertion of the regenerative snubber, the spike has been reduced to a very low value.
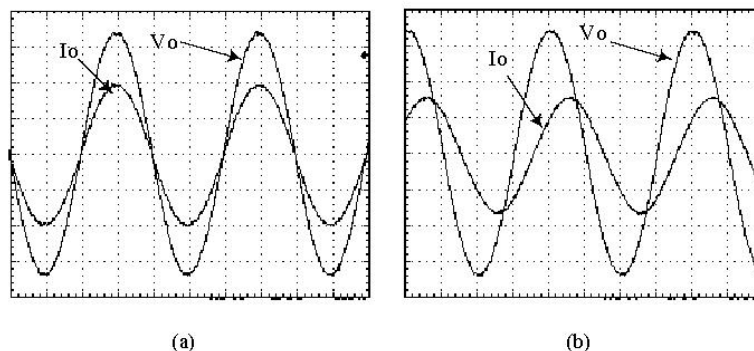


(a)                                    (b)

Fig. 7. Output voltage and current with (a) resistive load, (b)inductive load (power factor = 0.7)
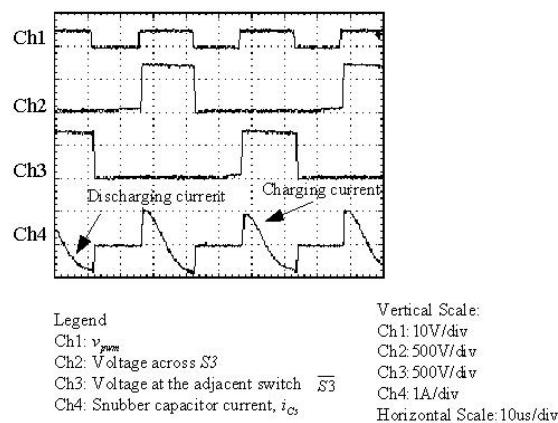Scales: output voltage 100V/div, output current 2A/div, time 5ms/div.



Legend
Ch1: $v_{pwm}$
Ch2: Voltage across $S3$
Ch3: Voltage at the adjacent switch $\overline{S3}$
Ch4: Snubber capacitor current, $i_{Cs}$

Vertical Scale:
Ch1: 10V/div
Ch2: 500V/div
Ch3: 500V/div
Ch4: 1A/div
Horizontal Scale: 10us/div

Fig. 8. The inverter is capable of conducting bidirectional power flow.

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Vertical Scale:
Ch1: 10V/div
Ch2: 800V/div
Ch3: 50V/div
Ch4: 350/div

Time Scale: 20us

Legend:
Ch1: Control signal for switch, *Ss*
Ch2: Transformer secondry voltage
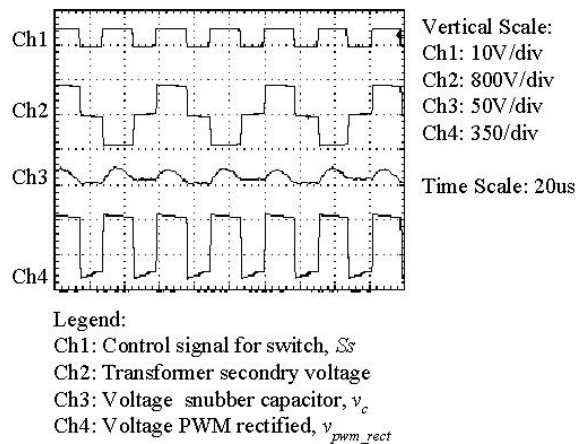Ch3: Voltage snubber capacitor, $v_c$
Ch4: Voltage PWM rectified, $v_{pwm\_rect}$

Fig. 9. Control signal of switch Ss and the associated output waveforms after insertion of regenerative snubber.



Vce of S3 without snubber
Vertical Scale:200V
Time Scale:5us
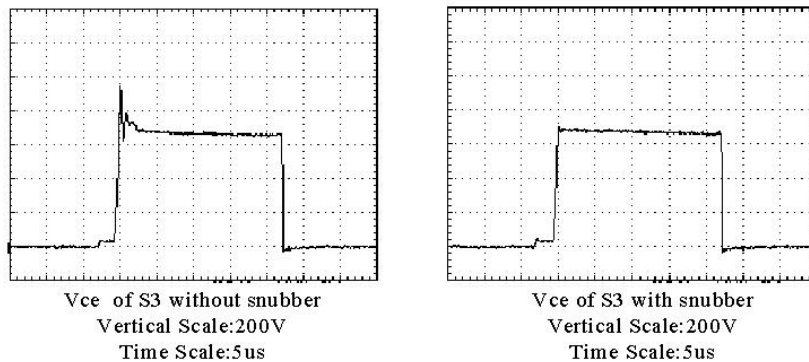
Vce of S3 with snubber
Vertical Scale:200V
Time Scale:5us

Fig. 10. Voltage Vce at switch S3 before and after the insertion of regenerative snubber.

Fig. 11 compares the inverter efficiency using regenerative snubber and the conventional RCD snubber. For the latter, the values of *Cs* and *Rs* are chosen to be 2.2 nF and 22 Ω, respectively. The chosen capacitor values for the RCD snubber components are rather conservative; typical values are much higher than this. From the figure, it can be concluded that the new snubber is able to increase the efficiency of the inverter by about 5%. A higher value for RCD components will make the difference even larger.
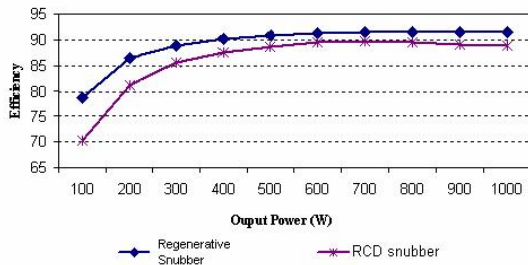


Fig. 11. Efficiency vs. output power

## IV. CONCLUSION

This paper has described the operation of a snubber network that is applied to a center-tapped active rectifier high frequency transformer. To prove the concept, a 1kW prototype inverter is constructed. From the experimental results, it was found that the snubber network function as predicted. The voltage spike across the active rectifier's switch is reduced significantly. Furthermore the efficiency of the inverter is increased.

## REFERENCES

[1] Koutroulis, E., and Chatzakis, J., "A bidirectional, sinusoidal, high-frequency inverter design," *IEE Proc-Electric Power App.*, vol. 148, no. 4, July 2001.

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