Spike Suppression in a Bidirectional High-Frequency Transformer-Link Inverter Using a Regenerative Snubber

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Keywords: Bidirectional, HF transformer, Inverter, Snubber, Spike suppression.

Abstract

This paper presents a spike suppression method for Bidirectional High-Frequency Link (BHFL) inverter using a regenerative snubber. Unlike the RCD snubber, this regenerative snubber dampens the voltage spike by charging its snubber capacitor during switch transition. The energy is then pumped back into the main power circuit. A 1kVA prototype inverter is constructed and the workability of the regenerative snubber is tested on the inverter. The results show that the voltage spike is significantly reduced. The efficiency of the inverter is also increased by about 5%.

1 Introduction

High-frequency link inverters have been applied in dc-ac power conversion in which size and weight are of important considerations. This type of inverter utilises the high-frequency transformer. Threfore, it is compact and light weight compared to the line-frequency transformer inverters. However, high-frequency link inverters also have an inherent problem of voltage spike at the transformer secondary. This is due to the leakage inductance at the transformer secondary. During switch transition, the current through the switch is turned off very quickly. Therefore, the di/dt is very high, resulting in high voltage spike to occur across the switch. If not properly handled, the voltage spikes may lead to switch destruction.

In our previous paper [3], a Bidirectional High-Frequency (BHFL) inverter using centre-tapped transformer has been described. The circuit has reduced number of switches compared to the topologies proposed by [1] and [2]. However, it is known that the voltage across the switch at transformer secondary is double in amplitude due to the centre-tapped configuration. As the voltage stress across the switch is already high, additional voltage spike can be harmful to the power switch. The common method to dampen the voltage spike is using a RCD snubber, as depicted in Figure 1. However, for adequate spike suppression, the required snubber capacitor, C_s can be quite large. As a result, high discharge energy will be dissipated in the snubber resistor, R_s when the switch turns back on. This mandates for the use of high power R_s, which causes further loss of inverter efficiency.

In this paper, we introduce a regenerative snubber that effectively reduces the voltage spike to a very low value. Owing to the lossless nature of the snubber, the energy in the voltage spike is stored in the snubber, and subsequently transferred back to the power circuit. As such, the overall efficiency of the inverter can be improved.

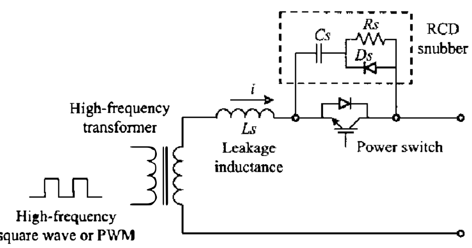


Figure 1: Spike suppression using RCD snubber.

2 System Description

2.1 Power Circuit

The BHFL inverter is shown in Figure2. The main conversion circuits are the high-frequency Pulse Width Modulation (PWM) bridge, active rectifier and polarity-reversing bridge. The dc voltage, V_{dc} is converted into high-frequency PWM voltage, v_{HF} using the high-frequency PWM bridge. Then, this voltage is isolated and stepped-up using the high-frequency transformer. Next, the voltage is rectified using the 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 to the load, the diodes are utilised; for reverse power flow, the power switches S3 and $\overline{S3}$ are turned on. The rectified PWM voltage, v_{pwm_rect} is then low-pass filtered, v_{rect} and unfolded to obtain the sinusoidal output voltage, v_o. The key waveforms at the principal conversion stages are shown in Figure 3.

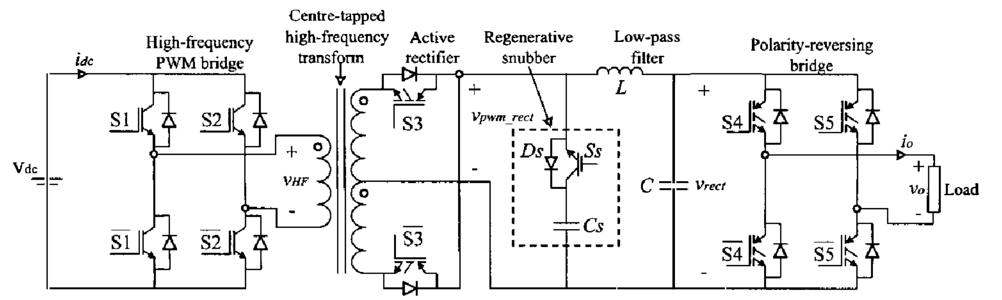


Figure 2: Bidirectional High-Frequency Link (BHFL) inverter with regenerative snubber.

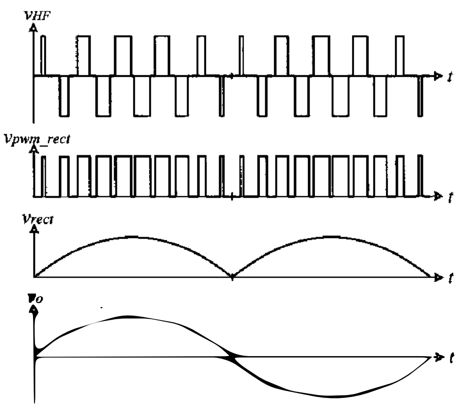


Figure 3: Key waveforms at the principal conversion stages.

Figure 4 shows the timing diagram of the gate control signals for the main conversion circuits. The control signal v_s is used to control the power flow at the active rectifier stage. Note that the frequency v_s is half of v_{pwm}. The control signal for polarity-reversing bridge is denoted as v_u.

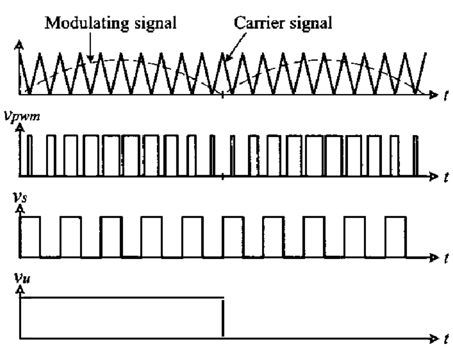


Figure 4: Gate control signals for BHFL inverter.

2.2 Regenerative Snubber

Owing to the presence of leakage inductance at the transformer secondary, substantial amplitude of voltage spike will be appear across the active rectifier switches during switching transitions. The voltage spike is developed as a result of high di/dt. The common practice to solve this problem is to dampen the voltage spike by placing a RCD snubber across the switches. For effective damping, a relatively large snubber capacitor and a high power resistor is required. Consequently, the energy will be dissipated in the snubber circuit, resulting in reduced inverter efficiency. In this work, we propose a regenerative snubber, as denoted by the dashed box in Figure 2. The aim of the snubber circuit is to reduce the voltage spike across the active rectifier's switches (S3 and $\overline{S3}$) to a safe level. It comprises of snubber diode D_s, snubber switch S_s and snubber capacitor C_s. The operating principle of the regenerative snubber and its corresponding timing diagram are shown in Figure 5.

When any of the active rectifier's switches is turned on, voltage spike will occur on the adjacent (off) switch. This is because the energy stored in the leakage inductance is released and appears as voltage spike with a sudden current turn-off. Referring to Figure 5, it is assumed that the snubber diode, D_s and snubber switch S_s are ideal. The voltage across the snubber capacitor, C_s without voltage spike is v_1. When voltage spike occurs, v_{pwm_HF} increases, thus D_s is forward biased and charges C_s. The snubber capacitor, C_s dampens the voltage spike by reducing its di/dt. The charging process from t_1 to t_2 causes the snubber capacitor voltage v_{cs} to rise. When v_{cs} equals v_2, i.e. when the snubber capacitor voltage equals to v_{pwm_HF}, the charging process stops. At this point, the snubber diode D_s is reverse biased. Subsequently, C_s begins to discharge its energy into the power circuit via S_s. The discharging process continues until end of the PWM pulse. When the PWM pulse has ended, S_s is turned off, and the discharging process stops. Voltage v_{cs} is maintained at its equilibrium level (v_1) until the next charging process takes place.

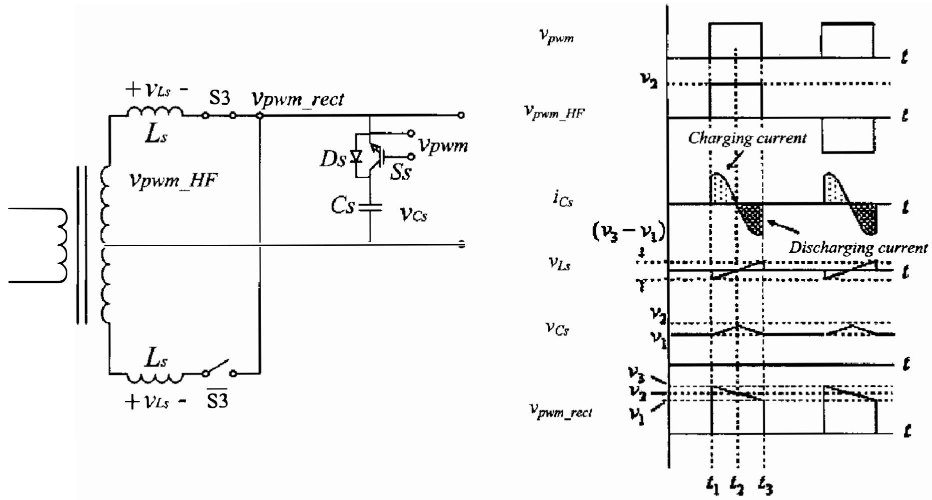


Figure 5: Regenerative snubber and its corresponding timing diagram.

3 Hardware Construction

A 1kVA prototype inverter has been constructed. The regenerative snubber has been incorporated with the power circuit. The high-frequency PWM bridge is built using the APT15GP60BDF1 power IGBT. The device has good switching capability with low conduction loss. The high-frequency transformer is wound around the ETD59 ferrite core. Ferrite core is chosen as it is the most suitable material for high frequency operations. The active rectifier is constructed using the IRG4PH40K IGBT and STTA1212D ultrafast high voltage diode. These devices have voltage rating of 1200V, thus suitable to be applied at the centre-tapped active rectifier. The polarity-reversing bridge is constructed using the IRG4PC40FD IGBT. As the voltage spike has been suppressed before the polarity-reversing bridge, the selected power switches are only rated at 600V. By using low voltage power switches, the forward conduction loss can be minimised. The regenerative snubber is built using the IRF730 MOSFET as the snubber switch S_s, and the snubber capacitor is chosen to be 2.2μF. All the power switches are driven by the HCPL3120 gate driver chip from Hewlett-Packard. This chip has a built-in optocoupler with power output stage, which is suitable for direct driving of power switches. This "all-in-one-chip" solution has simplified the interfacing process. The DS1104 Digital Signal Processor (DSP) from dSPACE (64-bit floating-point processor with TMS320F240 Slave DSP) is used to generate the control signals for the power switches. The control signals will then go through a series of external logic gates, shown in Figure 6, and become the input signals of gate drives.

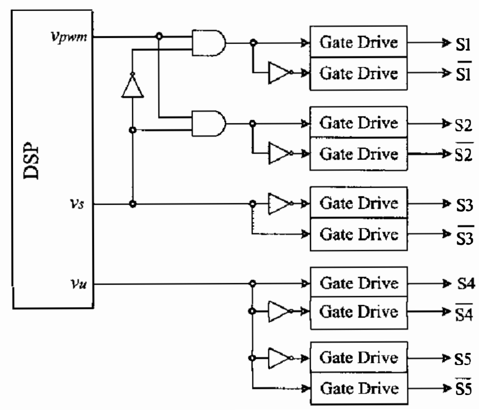
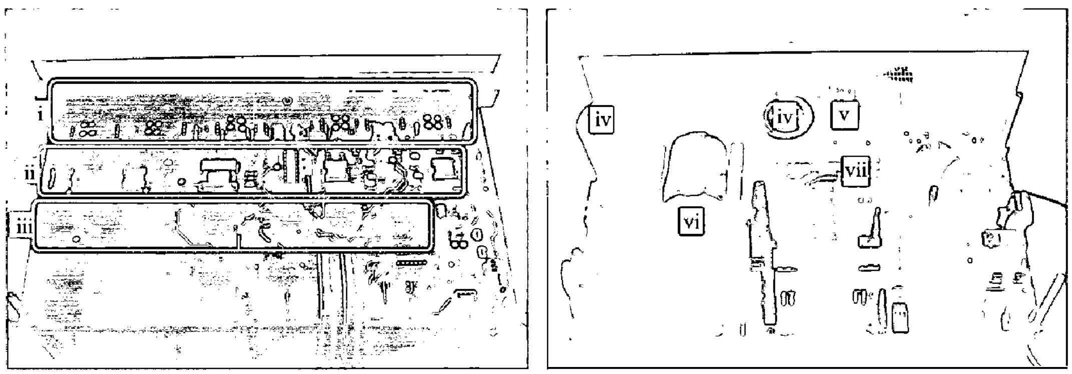


Figure 6: Interface between DSP and power switches.

The photograph of the constructed prototype inverter is shown in Figure 7. It is divided into two modules, namely the gate drive module and the power circuit module. To obtain an isolated power supply for the gate drivers, dc-dc converters driven by SG3526 pulse generator have been constructed with miniature high-frequency transformers. The transformers are designed such that there are two secondary centre-tapped windings. This ensures two units of gate drive power supply to be constructed with minimum components. Dead-time generators are also incorporated to provide sufficient time for complimentary switches to completely turn off.



(a) Top view – gate drive module

(b) Bottom view – power circuit module

Legend:
i. Power switches and gate drivers
ii. Gate drive power supplies
iii. Dead-time generators and logic gates
iv. DC link capacitors
v. Regenerative snubber circuit
vi. High-frequency transformer
vii. *LC* low-pass filter

Figure 7: Photograph of the prototype inverter.

4 Experimental Results and Discussion

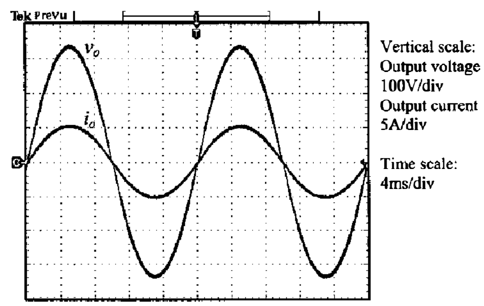
To verify the feasibility of the proposed spike suppression technique, the regenerative snubber has been tested on the prototype inverter. The specifications of the system are as follows:

- Nominal input voltage, $V_{dc} = 150V$
- Rated output voltage, $v_o = 240Vrms$
- Rated output frequency, $f = 50Hz$

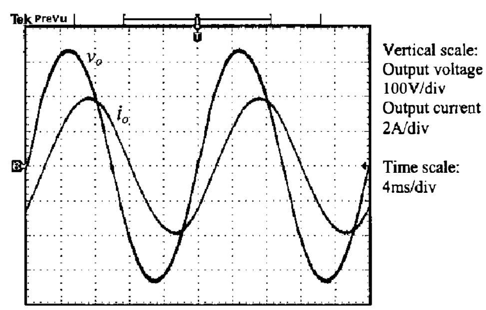
The output voltage and current waveforms under resistive and inductive loads are shown in Figure 8(a) and (b) respectively. Figure 8(b) indicates that the BHFL inverter is capable of carrying bidirectional power flow. Therefore, the BHFL inverter is suitable for stand-alone Uninterruptible Power Supply (UPS) applications.

Figure 9 depicts the key operation waveforms of the regenerative snubber. As can be seen, the snubber capacitor C_s is charged and discharged in synchronised with the PWM pulses. These results have close agreement with the theoretical prediction.

Figure 10 shows the collector-emitter voltage, V_{CE} at the active rectifier' switch (S3) before and after insertion of the regenerative snubber. It is obvious that before the insertion of regenerative snubber, the voltage surge is about 40% of the amplitude. After the regenerative snubber is inserted, the voltage spike has been reduced to a negligible level.



(a) Output waveforms under resistive load



(b) Output waveforms under inductive load

Figure 8: Output waveforms for resistive and inductive loads.

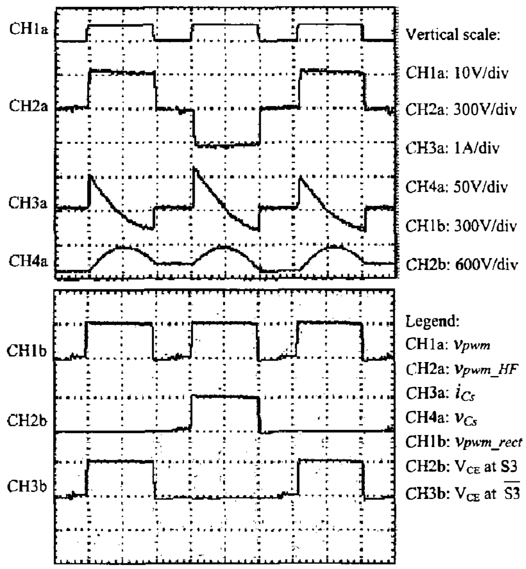
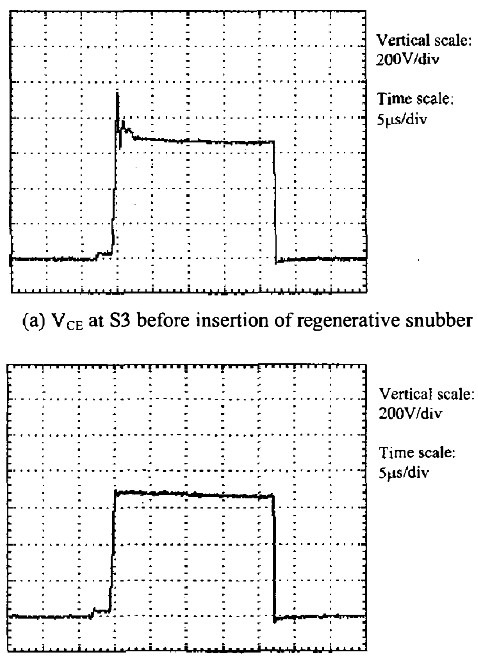


Figure 9: Key operation waveforms of regenerative snubber.



(a) V_{CE} at S3 before insertion of regenerative snubber

(b) V_{CE} at S3 after insertion of regenerative snubber

Figure 10: V_{CE} at S3 without and with regenerative snubber.

To verify the effectiveness of the regenerative snubber, the inverter efficiency is compared using the regenerative snubber and the RCD snubber. For the latter, the values of C_s and R_s are chosen as 2.2nF and 22Ω, respectively. These values are selected rather conservatively - typical values of C_s and R_s would be much higher. Figure 11 shows that the regenerative snubber is able to increase the inverter efficiency by about 5%. Note that higher RCD component values will make the difference even larger.

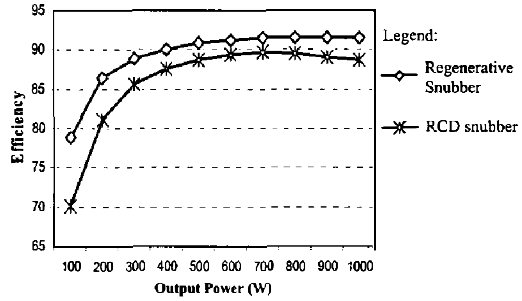


Figure 11: Efficiency vs output power.

5 Conclusion

A regenerative snubber for voltage spike suppression in the BHFL inverter has been described. To verify the viability of the proposed snubber, a 1kVA prototype inverter has been constructed. The experimental results show that the regenerative snubber functions as predicted. The voltage spike across the active rectifier switch is reduced to a safe level. As compared to the RCD snubber, the regenerative snubber has more superior performance. The overall efficiency of the inverter is increased by about 5%.

Acknowledgements

The authors wish to acknowledge the Ministry of Science, Technology and Innovation, Malaysia (MOSTI) for the financial funding of this project.

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