OVER-VOLTAGE PROTECTION OF SINGLE PHASE GRID CONNECTED CURRENT SOURCE INVERTERS USING A SIMPLIFIED PASSIVE NETWORK

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Abstract

Current source inverters (CSIs) feature additional attention, compared to voltage source inverters (VSIs), because of their advantages, like inherent current short-circuit proof and low output voltage THD. The major constrain for CSIs is the necessity of the DC-link current continuity. Transient over-voltage occurs in case of DC-link current interruption due to failure of IGBT/series diode/gate driver. The non-robust behaviour of IGBT at breakdown voltage makes fast over-voltage protection a must. Utilization of Varistors for CSI over-voltage protection is limited because of their flat v-i characteristics. Although active clamping techniques achieve steeper characteristics, several disadvantages are remarked like the need to install a protection circuit per each IGBT and the inability to proper operation if the IGBT is defective. Breakover diodes are also good candidate but their poor dynamic behaviour limits their application to slow rate Thyristor-based CSIs. In this paper, a simplified two-stage fast-acting passive over-voltage protection network is proposed for IGBT based CSIs. In addition to simulation, an experimental setup is implemented to validate the proposed circuit effective performance.

1 Introduction

The majority of recent renewable energy based inverters utilize voltage source inverter (VSI) as the main grid-to-source link. Recent designs, based on current source inverter (CSI), evolve promising performance from the output voltage/current power quality aspects in addition to lower filter requirement and inherent short-circuit proof [1-3].

As the DC-link of CSI is highly inductive, due to the built-in DC-link choke, the continuity of the DC-link current is a must irrespective of the used modulation technique [4-6].

Several issues lead to over-voltage transient for the CSI semiconductors mainly, short-circuit, over-current and current interruption. Among those issues, the DC-link current interruption is of special interest as most common faults occurs due to IGBT/Diode failure. This causes the energy stored in the DC-link inductor to rapidly increase the DC-link voltage, consequently further semiconductors could be destroyed [7, 8].

Over-voltage protection techniques can be either passive or active circuits. Passive elements, Varistors and Zener diodes, are widely used in inductive over-voltage transient protection. Low-voltage applications utilize Zeners while higher voltage demands use Varistors. Their finite non-steep v-i characteristics limit their applications in fast IGBT based CSI [8, 9]. Moreover limited energy handling capabilities are imposed by three common failure modes: puncture, thermal runaway and cracking [8, 10].

Breakover diodes (BODs) operate in a non conducting off-state, until the breakover voltage is reached. Then it starts conducting with a low forward voltage, until the current reaches its the minimum holding current. The static behavior of BOD is ideal for CSI protection, as the low drop voltage permits the DC-link choke energy to be dissipated without excessive thermal dissipation. At zero inductor current, the BOD automatically turns-off. The main demerit, which prevents BODs from being used for protection in IGBT based CSI**,** is their poor dynamic behavior. If their critical voltage rise rate (*dv/dt*) is reached, the BOD could accidentally turn on even if the breakover voltage is not reached. Moreover, the short voltage rise and fall times in IGBT circuits, makes BODs not applicable for fast switching converter protection. Hence, BODs are suited for Thyristor based CSI protection [11].

The utilization of the unidirectional Transient Voltage Suppressor (TVS) diodes, commercially known as Tranzorbs, is recently remarked. It clamps the voltage to a maximum value close to their nominal one with effects similar to a Zener diode. Nevertheless, very different from the Zener diodes, as they can dissipate high instantaneous powers for few microseconds and, their first failure mode are guaranteed to be a short circuit. The Tranzorbs are widely used as protection devices because of their clamping capabilities which are higher than Varistors [12, 13].

Active clamping techniques provide better response time, compared to Varistors, as much steeper v-i characteristics can be achieved. However it is required to equip all the CSI semiconductors with clamping circuits. Moreover, clamping technique fails if applied to a faulty IGBT. Furthermore, peak losses in the clamped IGBTs cause extreme thermal stress, which they typically cannot withstand unless the utilized IGBT is over-sized [8, 14].

A two-stage strategy was developed combining passive and active protection mechanisms [15]. The basic concept of this protection strategy consists of two stages. First is a fast hard voltage clamping network. Second is an actively turned-on freewheeling path across the DC-link terminals. The first stage dissipates the momentary peak power for at least the time; a freewheeling path needs to become active. At the same time, the clamping circuit is able to limit the voltage at full dc link current below the maximum rating of the IGBTs as hard limitation. The second stage starts conducting until the inductor energy becomes zero. This technique provides fast response time for voltage limitation and safe dissipation of the DC-choke energy. Compared to clamping of the DC-link voltage at a high voltage level, this technique reduces the momentary power dissipation at the expense of a longer time to get the inductor current to zero and relatively complex voltage clamping network [8, 15].

In this paper, a simplified passive-network-based over-voltage protection scheme for single phase CSI is proposed. The presented network utilizes Power Zener diodes as the detection element for over-voltage protection. Once detected, a shunt Thyristor-based short-circuit path is triggered to dissipate the stored DC-link inductor energy. The proposed technique offers robust fast response with simple construction.

The presented paper is organized in five sections. Following the literature review discussion in the introduction section, the proposed over-voltage protection scheme for single phase CSI is illustrated in the second section. The proposed technique simulation and experimental results are addressed and discussed in sections three and four respectively. Finally, a conclusion is given in the fifth section.

2 Proposed CSI over-voltage protection circuit

The block diagram of the single-phase CSI is shown in Fig. 1. Four IGBTs are used as the main switches with four series connected Fast Recovery Diodes for reverse blocking capability enhancement. The large DC-link inductor is mandatory for smooth almost-ripple-free DC-link current. The DC side can either be a renewable energy based converter or rectified sinusoidal voltage generated from a micro-generation. CL filter is required for low voltage THD grid connected applications. Also, the capacitor at the inverter output is essential for current commutation.

Any DC-link current interruption results in a fast over-voltage in the DC-link due to the inductor stored energy.

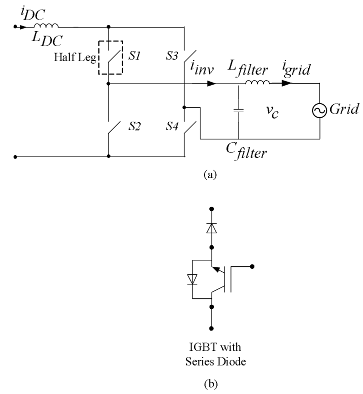


Fig. 1: Single phase grid connected CSI
(a) Topology, (b) Half-leg configuration

This interruption may be resultant from a switch/diode failure in the converter or the inverter side, mainly as an open circuit. This over-voltage is critical from both amplitude and rate (*dv/dt*) points of view. Hence, successive failure for the remaining switches/diodes occurs.

The proposed over-voltage protection circuit is shown in Fig. 2. From operation point of view, the circuit is divided into two paths/modes. Firstly, over-voltage is detected using the series connected Zener diodes. When the DC-link voltage suddenly increases, due to a DC-link current interruption and the DC-link voltage exceeds the Zener diodes clamping voltage, the series connected Zener diodes conduct to sustain the DC-link voltage at the required clamping safe value. This mode cannot be continuously operated as the thermal stress limitation of the Zener diodes cannot withstand the total dissipation of the DC-link inductor stored energy, therefore another path must then be operated. A shunt path, via a power Thyristor, is triggered as the next stage to dissipate the DC-link inductor stored energy. The resistance Rz is used to build a trigger voltage for the Thyristor while Rg controls the gate current. A relaxation capacitor is added to suppress any spikes that may false-trigger the Thyrisor. When the Thyristor path is triggered, the DC-link is short-circuited. This mode is of no harm as the system DC-link current is adequately controlled.

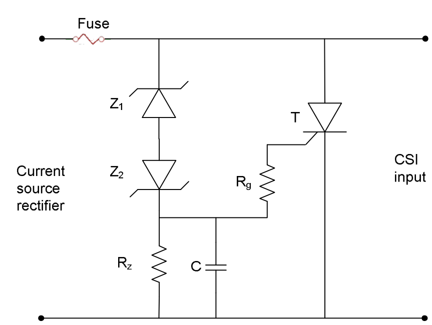


Fig. 2: Proposed over-voltage protection circuit

3 Simulation results

The proposed system MATLAB/SIMULINK model is shown in Fig. 3. The rectifier side is a voltage source current controlled converter. A single phase IGBT based CSI is utilized. Grid connection is established through CL filter. A proportional-resonant controller regulates the inverter grid current while a conventional proportional-integral controller is used for the DC-link current.

The simulated system runs at a 220 V, 50 Hz grid. The controlled DC-link current is 1 A. The CSI switching frequency is 3 kHz. Nominal peak DC-link voltage is nearly 320 V. The smoothing DC-link inductor is 10 mH.

The DC-link interruption is emulated using a momentary ideal zero-series-resistance switch.

As shown in Fig. 4(a), after 0.1 s a DC-link current interruption fault has occurred. In case of no over-voltage protection, the DC-link inductor stored energy causes high DC-link voltage rise as shown in Fig. 4(b). When an over-voltage protection scheme is applied for the same case, once an over-voltage is detected, a Thyristor based shunt short-circuit path is triggered. Hence, dissipating the DC-link inductor stored energy and prevents any rise in the DC-link voltage as shown in Fig. 4(d). Once the shunt path is triggered, the DC-link voltage becomes zero. Also, the DC-link current shows minimal transient effect as shown in Fig. 4(c).

4 Experimental results

In order to accurately verify the proposed circuit transient performance and validate its effectiveness, a low-voltage scaled-down test circuit is built to investigate the proposed circuit capability for over-voltage clamping in current source inductive applications as shown in Fig. 5. An LG GP-4303D power supply is used as a controlled current source. A DC-link inductor of 10 mH is inserted in series with the current source. Zener diodes BZT03C30, of 30 V clamping voltage is used. Higher clamping voltage can be achieved by series connection of Zener diodes. Zener diode series resistance (*Rz*) and Thyristor gate resistance (*Rg*) are 300 Ω and 57 Ω respectively. A capacitor of 1 μF is used for smoothing. A power Thyristor BT151 is shunt connected to the supply. The DC-link current interruption is performed using a manual switch.

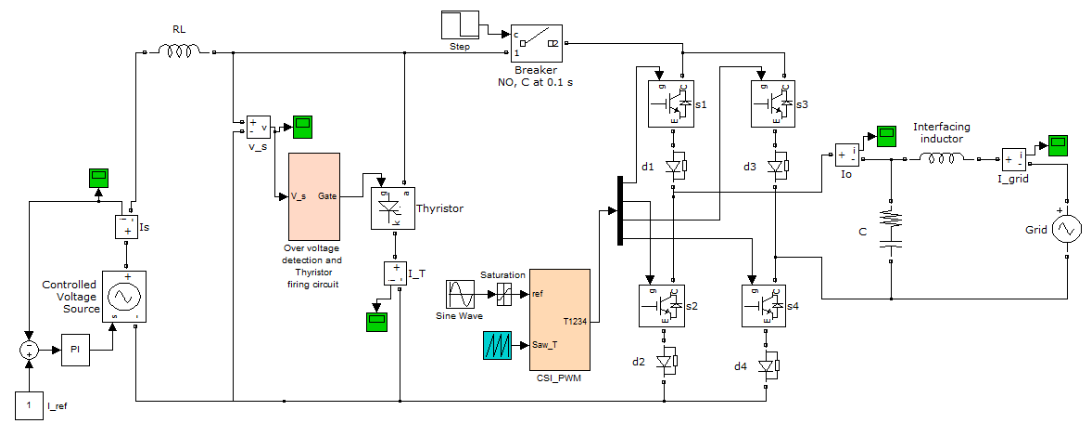
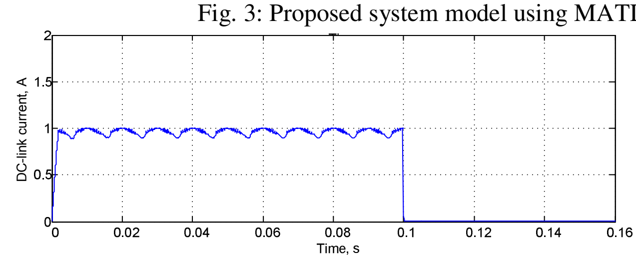
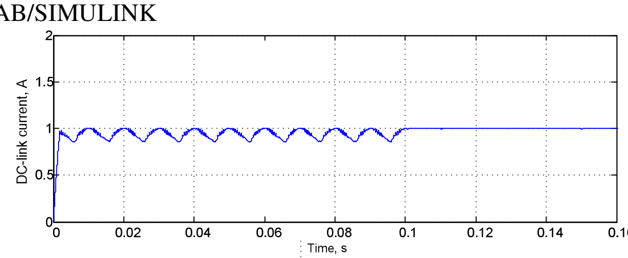


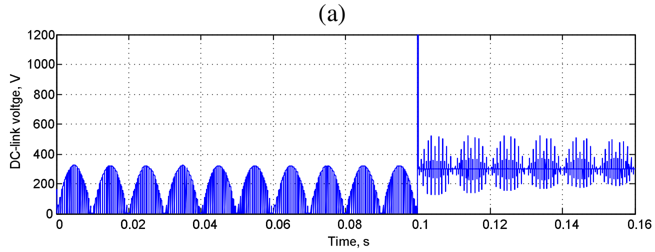
Fig. 3: Proposed system model using MATLAB/SIMULINK



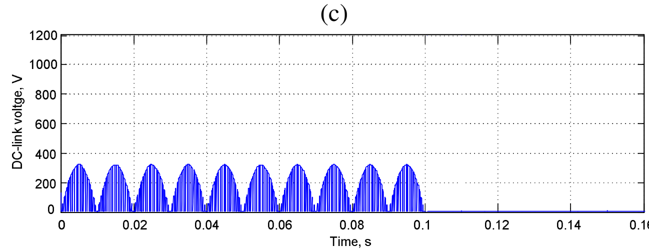
(a)



(c)



(b)



(d)

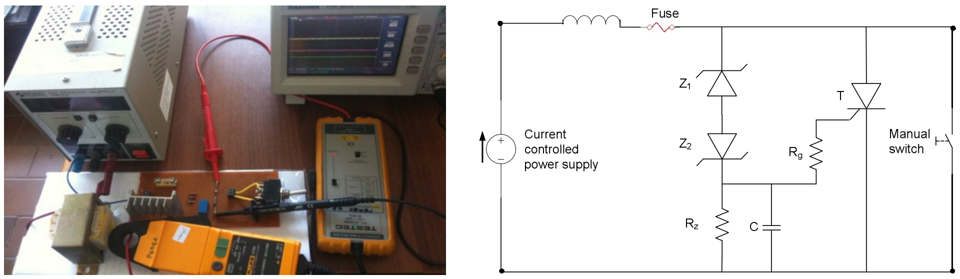
Fig. 4: Simulation results
(a, b) without over-voltage protection, (c, d) with over-voltage protection

As shown in Fig. 6, in normal operation, the switch is closed and a DC-link current of 2 A flows. Upon the switch opening, a DC-link interruption state is emulated. The DC-link voltage starts to increase. The instant the DC-link voltage reaches the Zener diodes' clamping voltage, 30 V, the Zener diode conducts to maintain the DC-link voltage constant.

During this short period of time, 8µs as indicated in Fig. 6(b), the whole DC-link current flows through the Zener path. This is typically the first mode of operation. As the Zener diode power capabilities are limited, the Thyristor shunt path must be triggered as fast as possible. Using Zener diode series resistance (*Rz*), Thyristor trigger voltage is initiated and the circuit second mode of operation starts.

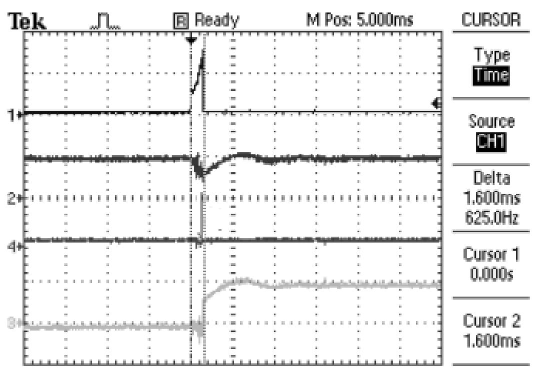
Once the Thyristor fully conducts, the DC-link current flow is transferred from the Zener path to the Thyristor path as shown in Fig. 6 and the DC-link voltage becomes zero.

Hence, the fast, µs range, operation of the proposed over-voltage protection circuit is proved experimentally with illustration of the smooth transfer between the two circuit modes.

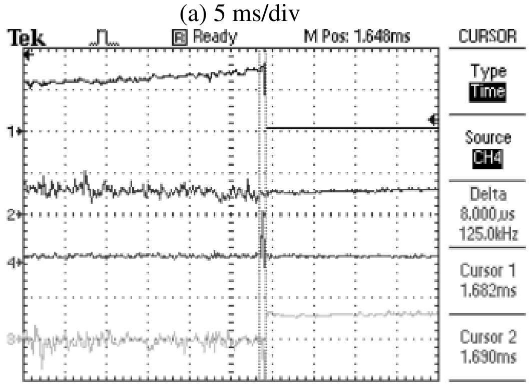


(a) (b)

Fig. 5: Test circuit experimental set-up
(a) test circuit photo, (b) schematic diagram



(a) 5 ms/div



(b) 50 µs/div *(zoom on part (a))*

Fig. 6: Proposed over-voltage protection circuit experimental results
(ch1) DC-link voltage, (ch2) DC-link current, (ch3) Thyristor current, and (ch4) Zener current
ch1: 20 V/div, ch2: 2 A/div, ch3: 2 A/div, ch4: 2 A/div

5 Conclusion

The CSI over-voltage due to DC-link current interruption has been presented. A simplified passive network is proposed. It operates in two stages, one for over-voltage detection and the other for maintaining a path for the DC-link current to dissipate the DC-link inductor stored energy. The proposed network offers simple realization, totally passive components used, no external power supply needed, and inherent non-retrigrrable fast latching capability. Simulation and experimental results validate the proposed system effectiveness.

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