Analysis and Simulation of Fault Tolerance of a Grid-connected PV Inverter by Z-source Impedance

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Abstract: This paper proposes the design of a monophasic inverter connected to a residential network by applying Z-Source topology. The proposed models were verified in normal operation “STC” and under short circuit conditions “SC”. The system is presented as coupled to a network without a transformer and with minimum electrical components. The tolerance of the overcurrent or short-circuit current is also analyzed on this topology. The signal’s power is conditioned to find the MPP of the PV panels. Its architecture will be outlined, described and simulated in Matlab’s Simulink®. In order to verify that the design is working properly.

1 INTRODUCTION

The failure analysis in power conversion equipment has become a critical focus of study in different types of industrial applications (Cordeiro et al, 2011; Tajfar and Mazumder, 2012). Current developments for photovoltaic installations connected to the grid, due to factors such as declining costs of solar panels and decentralized power generation, offer a greater market potential, making them competitive with conventional energy sources. Guaranteeing the continual operation of the system is of vital importance, therefore making the fault tolerance analysis for this type of systems of vital importance as well (Tajfar and Mazumder, 2012; Chavan and Chavan, 2014).

Among the faults that can be found in power converters are the electrolytic capacitors which are very susceptible to fault in the systems. In order to continue the order of importance, we have the switching devices which groups the semiconductors, the control circuit, the ceramic capacitors, the diodes and the inductors (Chan-Puc et al, 2009).

These devices perform the photovoltaic energy conversion using only electrical components which increases operational longevity when functioning correctly. The power converters being the most vulnerable to faults according to reliability studies (Petrone et al, 2008; Dhople et al, 2012), its capacity for fault tolerance reduces unit degradation and increases performance. However, its cost, weight, and size make its operation increasing complex because the system requires more components, making future improvements to overall system performance a challenge for the future, including aspects of lifetime performance of the integrated components in order to reduce losses and increase reliability (Cordeiro et al, 2011; Petrone et al, 2008; Tuan et al, 2012)

Connecting to the grid without the use of a transformer is an increasingly popular alternative where new topologies are studied in order to develop solid state architecture, mitigate problems associated with the galvanic connection between the grid and the PV generator, and reduce size and wear (Tuan et al, 2012; Patrao et al, 2011).

As new power conditioning strategies are proposed ZSource topology is of special note because studies have shown that it increases conversion efficiency by 1% compared with existing systems and the inverter system by 1% to 15% in comparison to conventional PWM inverters depending on their use (Patrao et al, 2011; Meinhardt and Mutschler, 1995).

This article proposes a study of photovoltaic generation connected to a residential grid, using a simple fault tolerant topological system in order to increase reliability in the VSI. As a method for conditioning solar power, an innovative design is attached to the inverter which is used to adjust the voltage levels at the inverter input to maximize the energy extracted from the solar panels, allowing a connection to the grid without a transformer

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(Cordeiro et al, 2011). This design is known in academic literature as ”Z inverter”. Its two inductors connected in series between the DC source and inverter allow the limitation of the di/dt variance of the device, giving the system time to disconnect and avoid damage or destruction of the system (Peng, 2003; Milady et al, 2009).

2 DEVELOPING

2.1 Z-source Topology

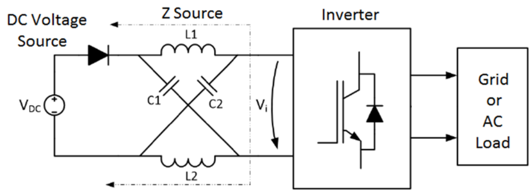

Figure 1: General configuration of a Z Source Inverter (Hanif, Basu &Gaughan, 2011).

Its topology (Figure 1), allows the coupling between the AC/DC inverter and the primary DC power source through an LC filter forming an ”X” between two inductors and two capacitors, usually with a smaller capacity than those used in an equivalent conventional converter, a diode then directs the DC source current to flow only towards the load. With this configuration, a short-circuit will not destroy the system, compared with other types of power converters, with Buck– Boost functioning stages in the same device allowing the application of voltage and current source inverters without needing to change the system topology (Peng, 2003; Zope et al, 2010; Hanif et al, 2011).

2.2 Z- source Function

A conventional single-phase inverter has 4 operating states, the Z inverter, allowing an additional operational state called Short Through or ”ST”, the Z Source Inverter has 5 operational states ”ZSI” are classified by 3 operational modes, as detailed in Figure 2 (Peng, 2003; Hanif et al, 2011):

1) Mode 1: The inverter is operating within normal operational states, the current circulates through the load, this mode is represented by an equivalent circuit, represented by a current source as shown in Figure 2 (1). The DC voltage source appears across the Z-network inductor and capacitor. The capacitor charges (kept in a charged steady state), the inductor is discharged and energy flows through this to the load (Zope et al, 2010; Hanif et al, 2011).

2) Mode 2: The Bridge AC / DC operates in zero states, the higher or lower switches short-circuit the charge through the device, leaving the load in open circuit. Its equivalent circuit is a source of zero amplitude current ”open circuit” as shown in Figure 2 (2). The DC source voltage appears across the inductor and capacitor (Bost stage), no current flows to the load (Zope et al, 2010; Hanif et al, 2011).

3) Mode 3: Running on ST inverter the switches short the Z network, as shown in Figure 2 (3). The load voltage is zero, the capacitor charge time (T_0) of the ST required. This interval is inserted in the states zero of mode 2, allowing the voltage boost whenever the photovoltaic panel is unable to provide the required voltage for any voltage drop due to changes in temperature or insulation. It should be taken into account that $V_d > V_{PV}\ y\ V_d = 2V_C$, at this moment the voltage in capacitors charges the inductors (Zope et al, 2010; Hanif et al, 2011).

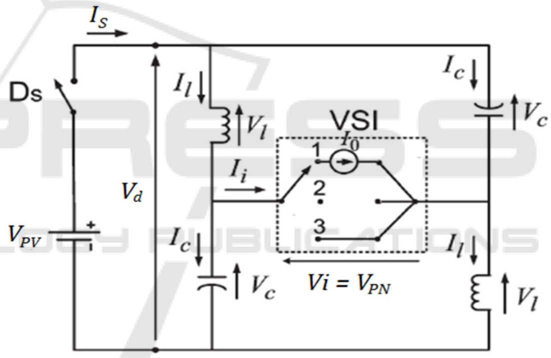

Figure 2: Equivalent circuits of Z Source Inverter (Rajakaruna and Jayawickrama, 2010). (1) Mode 1, (2) Mode 2 and (3) Mode 3.

2.3 Simple Boost Control (SBC) MATH

The SBC method proposed by Peng (Peng, 2003), is a control method for the ZSI based on traditional PWM modulation where two horizontal reference lines called V_P and V_N are added to the carrier signal and modulation. These two reference lines are compared with the carrier to generate the ST time of the Z converter. These levels must be higher than the amplitude modulation index, so that the ST mode does not interfere with conventional single-phase modulation PWM inverter. Limiting the ST value of the modulation index and meets the condition $V_N = -V_P$.

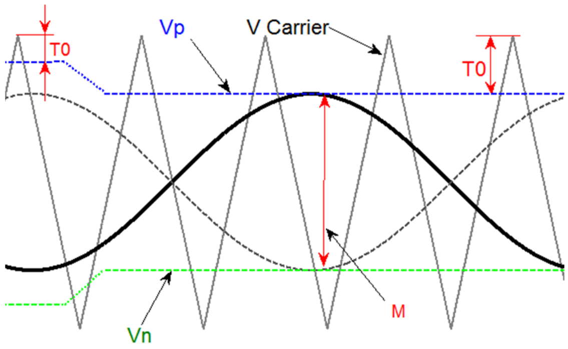

Figure 3: Switching time with "SBC" control method (Zope, 2012).

2.4 Maximum Power Point Tracking Strategy

The nonlinear characteristic of the photovoltaic modules means that its maximum power point cannot be reached by connecting directly to the load. For the proposed system the P&O algorithm was been chosen, a commonly used method, effective and easy to apply.

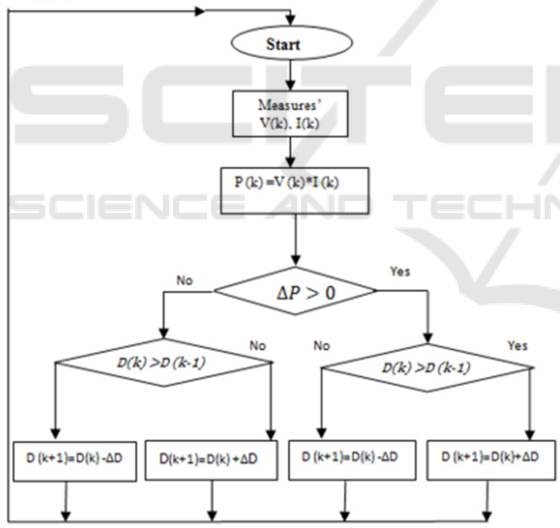

Figure 4: MPPT P&O Algorithm (Rajakaruna and Jayawickrama, 2010).

If the reference voltage V_{pv}, in the PV array is disturbed in one direction and the power produced by the same increases, it means that the operating point has moved to the MPP, therefore the operating voltage must be moved in the same direction, otherwise if the power extracted from the PV array decreases, the operating point is moved in the direction opposite the MPP location, therefore the operating voltage must be moved in the opposite direction, allowing the system to have a built-in signal conditioning and connecting directly to the residential grid, achieving maximum continuous power transfer from the PV panel to the grid or to the load (Hanif et al, 2011).

2.5 Modelling Z-Source

Assuming inductors $L1 = L2$ and capacitors $C1 = C2$, the mathematical equations that describe the converter operating parameters for SBC Control Z are (Hanif et al, 2011; Zope, 2012):

$$\widehat{V_{AC}} = \frac{M\widehat{V_{PN}}}{2} = \frac{M\,BV_{PV}}{2}, \quad (1)$$

$$T_0 = \frac{B-1}{2B} * T, \quad (2)$$

$$VC = \frac{B+1}{2} * V_{PV} \quad (3)$$

1) Design of Inductor: In normal operation of the inverter mode 1, the inductor current decreases linearly and its voltage is the difference between the input voltage PV and the capacitor voltage. At this point the input voltage appears in capacitors and a small DC current flows through the inductors.

During mode 2 when operating in Buck – Boost mode the function of the inductor is to limit ripple current, and finally in the ST mode, or operating mode 3, the current inductor increases linearly and the voltage across the inductor is equal to the voltage across the capacitor (Peng, 2003; Hanif et al, 2011; Zope, 2012). According to these considerations the inductance is calculated:

$$L = \frac{V * T_0}{\Delta L} \quad (4)$$

$\widehat{I_L}$ is the maximum current in the inductor, $\breve{I_L}$ is the minimum current in the Inductor

Where, $\Delta L = \widehat{I_L} - \breve{I_L}$ and T_0 is the time to ST

2) Capacitor Design: The function of the condenser is to absorb the ripple current and to be able to stabilize the voltage giving a quality sinusoidal wave to the inverter output. The capacitor is charged during the ST period, also as explained above in mode 3 the current through the capacitor and inductor are equal $I_L = I_c$ (Rajakaruna and Jayawickrama, 2010; Zope, 2012). In order to define the specifications of the voltage ripple in the capacitor ΔVC, we must consider a tolerance about 3% of the peak voltage according to the specifications given in many applications where Z converters have been designed (Rajakaruna and Jayawickrama, 2010; Hanif et al, 2011). In this manner, the condenser value could be estimated as:

$$C = \frac{\overline{I_L} * T_0}{\Delta V_C} \quad (5)$$

Where T_0 is the ST period, $\overline{I_L}$ is the average current through the inductor, and 4VC is considered 3% of VC.

2.6 Modelling and Simulation

1) Characteristic PV Panel Curve: Considering the standard operating conditions "STC" $T = 25C°$; $I = 1000\frac{W}{m^2}$, the values of the photovoltaic panel MPP are: Voltage $MPP = 220\,V$, $MPP\ Current = 40$ A Power $MPP = 8800\,W$, as shown in Figure 5:

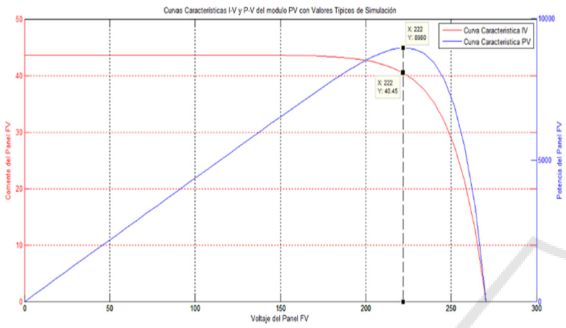

Figure 5: Characteristic curve PV Panel in "STC.

From the characteristic values of the PV panel the maximum current through the Z inductor is obtained, which corresponds to 30% of the average current $\overline{I_L}$.

2.7 Modeling Z-source

To know the maximum boost factor B, it is necessary to know the peak output voltage $\widehat{V_{AC}} = 294\,V$, the $V_{RMS} = 208\,V$, and the modulation factor $M = 0{,}6$, $V_{PV} = 230\,V$, using the equation (1):

$$B=\frac{2\widehat{V_{AC}}}{V_{PV}*M}$$

$$=\frac{2*294}{220*0{,}6}$$

$$=4{,}45$$

For a frequency modulation of 10 kHZ, the time T_0 of ST according to the equation (2) is:

$$T_0 = \frac{B-1}{2B}*T$$

$$=\frac{4{,}45-1}{2*4{,}45}*(1*10^{-4})$$

$$=39{,}76\ \mu s,$$

It should be noted that the maximum T_0 can be inserted in mode 2 without any problem. The maximum voltage the Z capacitor using equation (3) is:

$$VC=\frac{B+1}{2}*V_{PV}$$

$$=\frac{4{,}71+1}{2}*230$$

$$=599{,}5\ V.$$

The capacitor voltage provides the maximum values supporting the DC bus and the switches of the inverter bridge when in open circuit. With equation (4), the value of the Z network inductance is calculated.

$$L=\frac{VC*T_0}{\Delta L}$$

$$=\frac{599{,}5[v]*39{,}76[us]}{24}$$

$$\cong 1\ mH,$$

To calculate the Z-source capacitor, use the Equation (5).

$$C=\frac{\overline{I_L}*T_0}{\Delta V_C}$$

$$=\frac{40[A]*39{,}76[us]}{0{,}03*599{,}5}$$

$$\cong 88{,}4\ uF$$

The equations used for the analysis are approximations of the Z converter and do not consider factors such as transience due to switching, resonant transience, or component resistances, so that resonances not predicted in the design are occurring. According to information obtained in literature (Zope et al, 2010; Das et al, 2008; Shen et al, 2006), the converter stability output voltage can be increased by a capacitor of 1000 uF.

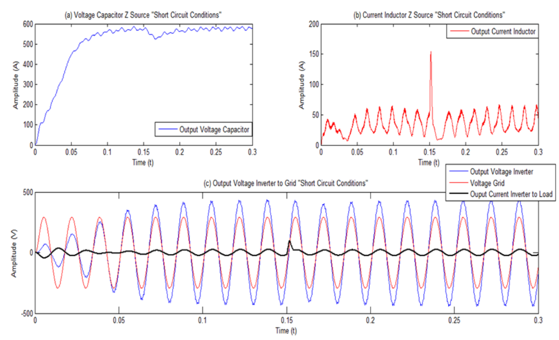

Figure 6: Characteristic Curves of VZI in "STC".

The AC output voltages connected to the network shown in Figure 6 are very close to those calculated.

1) **Fault Tolerance Test:** When a short circuit occurs in a conventional inverter "VSI" without Z network, it produces a sudden change in current over time di/dt, as shown in Figure 7. A high current short-circuit is generated in a short time putting the system at risk, due to a delayed protection response which in the best of cases produces strain on the components or total destruction of the system.

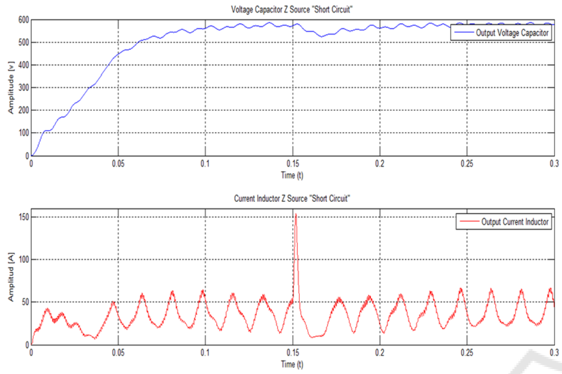

Figure 7: Output of "VSI" in Short Circuit Conditions.

Upon the contingency of a short-circuit in the proposed VZI system, as shown in Figure 8, the Z network responds as we expected, attenuating the variation di/dt. This helps to allow the system Protection the time needed to react without destroying the enabled devices. In addition, if the failure is dissipated before the protection activates, the inverter can continue to operate normally as the Z network does not allow the current to instantly rise to destructive levels.

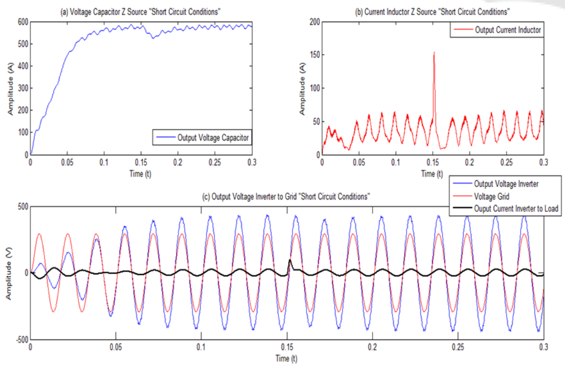

Figure 8: Ouput Waveforms from VZI "Short Circuit Conditions".

3 CONCLUSIONS

This paper proposes and analyzes a photovoltaic system connected to the grid with a new fault-tolerant topology.

The proposal combines an efficient topology fault coverage, reduces stress on the components, and increases the availability of power compared to conventional photovoltaic inverter systems.

System behavior is analyzed via simulations in STC and short circuit conditions, which reveals the characteristic advantages offered by the Z Source inverter. The results revealed that the Z network can provide effective protection against short circuit, decreasing the variation di/dt in the system, allowing enough time for the system protection to intervene. With this feature, the system can withstand short circuits without harming the operation or performance of electronic devices.

This architecture is a good alternative for applications in PV systems, for improving reliability of these systems without increasing the number of components and reducing the associated costs, and improving the conversion efficiency of the inverter compared to classical topologies.

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