

# Design and Operation of Z-Source Virtual synchronous generator In PV System

Madhusa<sup>1</sup>, Arpula. Krishnaiah<sup>2</sup>, Maisakhsi.Pavan kumar<sup>3</sup>

<sup>1</sup>Electrical and Electronics Engineering & KLR Engineering College, Palvancha, Telangana

<sup>2</sup>Electrical and Electronics Engineering & KLR Engineering College, Palvancha, Telangana

<sup>3</sup>Electrical and Electronics Engineering & KLR Engineering College, Palvancha, Telangana

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## Abstract

*The dynamics of large-scale power systems are changing quickly because of the growing involvement of power-electronics-based distributed energy resources (DERs) which are slowly replacing the traditional synchronous generators. Consequently, the power grid has less inertia, damping of oscillation and supporting voltages thus restricting its capacity to deliver the necessary ancillary services e.g. voltage and frequency regulation. This paper introduces a multi-mode operation plan of a Z-source virtual synchronous generator (ZVSG). The proposed converter involves the use of a Z-source inverter that has the ability to track the frequency as well as provides a better stability when the virtual inertia is simulated. The added inertia helps in better system protection and stability on making the frequency change rate higher. Additionally, the converter is meant to provide the important grid support services both when the grid is operating normally and when there is a grid fault situation. In the normal operation, the ZVSG operates in maximum power point tracking (MPPT) mode, whereby it injects the maximum power that can be offered by the photovoltaic (PV) system into the grid. In grid disturbances, there is the activation of low-voltage ride-through (LVRT) control strategy, which allows the system to provide reactive power towards the restoration of voltages in accordance with grid codes and standards.*

**Keywords:** Impedance-source inverter, virtual synchronous generator, photovoltaic (PV) systems, low Voltage ride through.

## 1.Introduction

Power electronics interfaces on distributed generators (DGs) have been more widely incorporated into the current power systems to improve grid performance and reliability (1). Nevertheless, the actual implementation of such DGs has greatly changed the dynamic behavior of the power grid. Specifically, the grid loses oscillation damping, voltage support and inertia (2), (3). The total inertial constant of the power system is greatly decreased as only power-electronic interfaces are not tied to rotating masses and do not store kinetic energy (4). This inertial loss causes the rate of change of frequency (RoCoF) to increase, which increases the susceptibility of the grid to perturbations to the degree that it might provoke RoCoF protection relays, even during minor events (5).

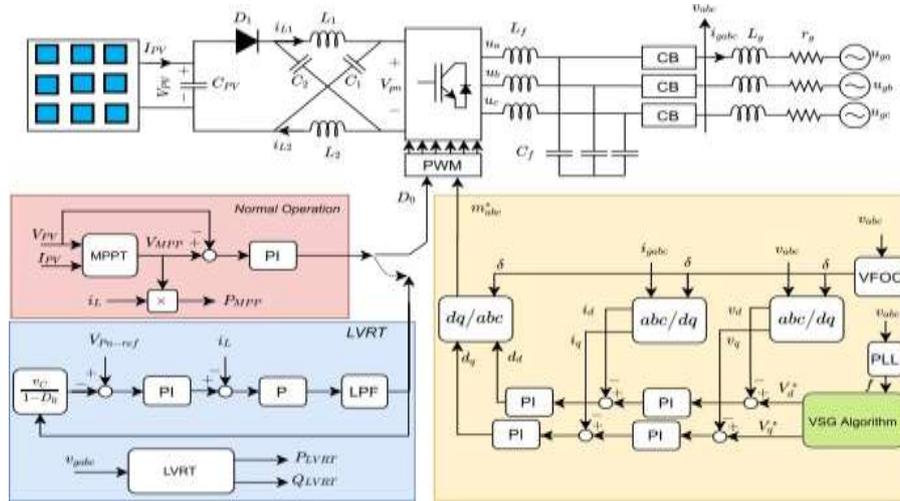
To solve the problem of decreased inertia, inertia emulation, in which the inverters replicate the dynamic behavior of the synchronous generators (SGs), was proposed in (6). Virtual inertia added to the converter control loops allows a drastic enhancement of power oscillation damping, frequency response and overall grid stability. Detailed discussion of the virtual synchronous generator (VSG) control strategies is presented in (4), (7). Majority of these approaches are intended to model the transient features of the SG swing equation (8). Although VSG-based control measures are successful in curbing frequency related disturbances, other protection mechanisms are needed to counter voltage related grid faults (9).

Grids codes require DGs to supply ancillary services, especially reactive power assistance, to make sure that the grid is supported during such disturbances especially in and sustaining the voltage stability in the event of a fault condition (10). As a result, low-voltage ride-through (LVRT) of grid-connected photovoltaic (PV) systems has been widely studied in literature (9), (11) -(16). As an example, (16) proposed an adaptive control strategy to control gains of the controllers online without solving an optimization problem, and (12) proposed an optimization-based method to increase the harvested energy under normal and LVVT conditions. The VSG control has also been applied to LVRT capable two-level voltage source inverters (VSIs).

The first converters to use impedance-source were impedance-source inverters (ZSIs) which are highly used in grid-connected PV systems, and grid fault mitigation, such as LVRT (22)-(27). As an example, (28), (29) suggested using a strategy of vector current control, compensating a negative-sequence grid voltage in the

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feedforward mode, to bring grid voltage to its nominal value. Such techniques may be useful to fix voltage sagging, but the reactive injected current to meet LVRT needs may cause too much current stress on converters when the grid voltages are imbalanced (30). PV systems can disconnect themselves to the grid to prevent this overcurrent stress, but disconnection can worsen fault conditions because it minimises active power generation and enhances grid stability even further (31).



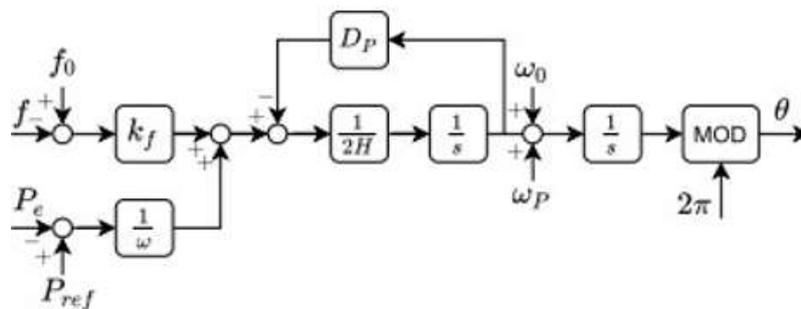
**FIGURE 1** Proposed ZVSG Converter Equipped with VSG and LVRT Control Algorithms

The ability of ZSIs to offer grid ancillary services has been examined before, but the capability to simulate the effect of virtual inertia has not been examined properly. The paper discusses a Z-source virtual synchronous generator (ZVSG) as an integration to the merits of ZSI topology, virtual inertia emulation, and ancillary services provision as shown in Fig. 1. Performance of the system is assessed during normal operation of the system and grid fault conditions. At normal operation, the ZVSG works in the maximum power point tracking (MPPT) mode and delivers the maximum achievable power of the PV panels to the grid. In the case of voltage sag events, the constant peak current control strategy is used to allow operation of the LVRT. This will make sure that the necessary active and reactive power is injected in accordance with grid codes, the current does not exceed the specified allowable limits of the grid-connected converter.

## 2. Proposed Control under Voltage Sag

### 2.1 Introduction

As discussed in Section I, the proposed Z-source virtual synchronous generator (ZVSG) is capable of operating in multiple modes. This section focuses on the control strategy adopted to restore grid voltage during voltage sag events. Upon detection of a grid fault, the photovoltaic (PV) control system must reduce the active power output; otherwise, the reactive power required for voltage recovery may exceed the converter's current limit, leading to increased stress and higher maintenance costs. To address this issue, the ZVSG transitions from normal maximum power point tracking (MPPT) operation to low-voltage ride-through (LVRT) control mode. This transition requires coordinated modifications to both the DC-side and AC-side control strategies.



**FIGURE 2** The Modified VSG Control Loop with including w p angle for grid Connection Pre-synchronization

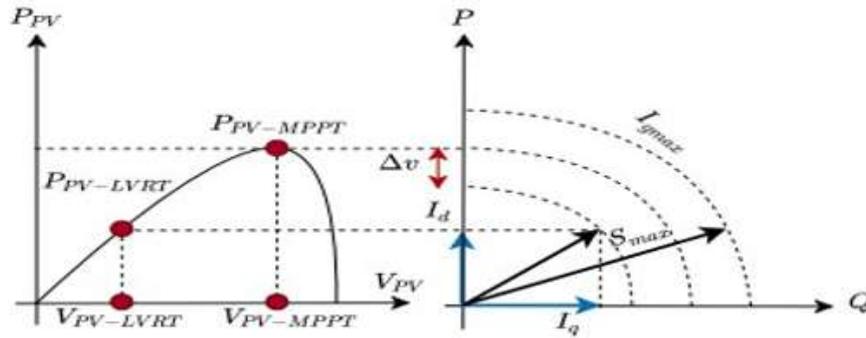


FIGURE 3 Regulating reactive power during LVRT

**2.2 DC-Side Control**

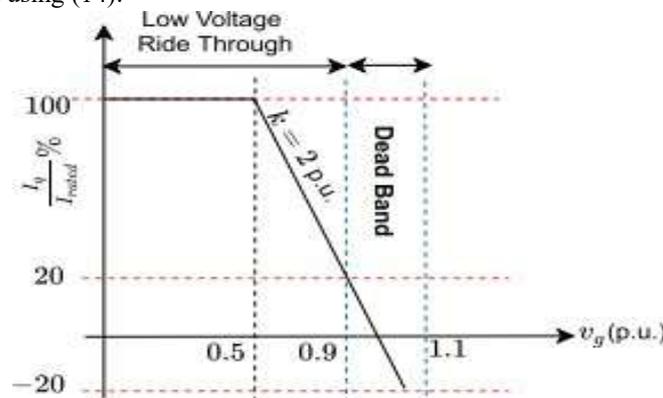
During grid faults, the ZVSG no longer operates in MPPT mode; therefore, an alternative DC-side control strategy is required to regulate the DC-link voltage and generate the appropriate shoot-through duty cycle, D0D\_0D0. An indirect control approach is employed to regulate the voltage and current of the impedance network. In this scheme, an outer control loop tracks the reference voltage  $V_{pn-ref}$ , while an inner proportional control loop regulates the inductor current  $i_{Li}$ . The inner current loop improves transient current control and enhances the overall stability margin of the system during fault conditions.

**2.3 AC-Side Control**

The proposed AC-side control strategy enhances voltage stability during grid faults by injecting reactive power into the grid. As noted in Section I, regulating reactive power alone may cause the grid current to exceed its permissible limit, potentially triggering overcurrent protection or damaging the converter. To prevent this, the peak amplitude of the injected grid current is maintained at a constant value to ensure safe operation.

Under normal conditions, the system operates in MPPT mode. Once a grid voltage disturbance is detected, the controller switches to LVRT mode, as illustrated in Fig. 7. After this transition, the system is capable of withstanding voltage sags for a limited duration. During LVRT operation, the required reactive power is injected to restore the grid voltage, while the active power output is simultaneously reduced to keep the peak current constant.

The reactive power requirements specified by the E.ON grid code are shown in Fig. 8, where the amount of reactive current depends on the grid voltage  $v_g$ . The maximum current that the ZVSG can inject during a voltage sag,  $I_{gmax}$ , is equal to the rated grid current  $I_{rated}$ . For a gain factor of  $k=2$ , if the grid voltage drops to 50% of its rated value ( $v_g \leq 0.5$  p.u.), the converter allocates its entire current capacity to reactive power injection, resulting in  $i_q = I_{rated}$ . Voltage variations within a dead band of  $\pm 0.1$  p.u. are considered disturbances rather than faults. Since  $I_{rated}$  is assumed to remain constant, the required direct-axis current  $i_d$  can be calculated using (14):



**3 Simulation Results**

The performance of the proposed Z-source virtual synchronous generator (ZVSG), shown in Fig. 1, is evaluated under various operating conditions, including steady-state operation, sudden load variations, and voltage sag

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events. The system and control parameters used in the simulations are summarized in Tables 1 and 2. The converter and associated control algorithms are modeled in MATLAB/Simulink using the Sim Power Systems toolbox. The converter switching signals are implemented on an OP5607 Virtex-7 FPGA module with a sampling time of  $T_s=0.1 \mu\text{s}$ , while real-time simulation results are obtained using the OPAL-RT digital simulator. The control loops are executed on the OP5600 module with a sampling time of  $T_s=10 \mu\text{s}$ . The selection of sampling times for each module is based on the complexity of the control algorithms and the required dynamic performance.

Accordingly, the performance of the ZVSG is assessed based on the following criteria: (i) reactive power injection during low-voltage ride-through (LVRT) operation in compliance with the E.ON grid code, (ii) maximum power extraction during steady-state operation, and (iii) enhancement of the system's rate of change of frequency (RoCoF) to improve the frequency stability margin [37].

### 3.1 Frequency Regulation

In this scenario, the ZVSG operates in MPPT mode. Figure 9 illustrates the RoCoF response of the converter following a step increase of 0.2 p.u. in active load at  $t=1$  s. Figure 9a shows the RoCoF profiles for different values of the virtual inertia constant  $H$ . As observed, lower values of  $H$  result in a higher RoCoF, leading to steeper frequency deviations. Larger RoCoF values increase the risk of triggering RoCoF protection relays, which may cause distributed generators to disconnect from the grid. A similar impact can be achieved by varying the damping coefficient  $D_p$ , as demonstrated in Fig. 9b.

### 3.2 Grid Connection

The inrush current behavior of the ZVSG during grid connection is illustrated in Fig. 10. Figure 10a shows the grid current waveform when the ZVSG is connected to the grid without pre-synchronization control, resulting in a high transient inrush current. In contrast, Fig. 10b presents the current waveform when the proposed pre-synchronization strategy described in Section III-C is applied. In this case, a significantly reduced peak current and smoother transient response are observed, with the peak inrush current reduced by approximately 2200 A.

### 3.3 Voltage Regulation

The overall system performance before, during, and after a grid fault is shown in Fig. 11. Under normal operating conditions, the system operates at unity power factor, as illustrated in Fig. 11a. At time  $t_1$ , a three-phase fault occurs, causing the grid voltage to drop to 0.75 p.u., as depicted in Fig. 11c. Once the voltage sag is detected, the controller transitions to LVRT mode, where new active and reactive power references are calculated based on the grid code requirements and the severity of the voltage sag. Consequently, as shown in Fig. 11d, the ZVSG injects reactive power to support voltage recovery, restoring the grid voltage at time  $t_2$ . After the grid voltage stabilizes at its rated value, the controller switches back to normal MPPT operation. Throughout the transition between MPPT and LVRT modes, the amplitude of the grid current remains constant, ensuring that the converter operates within its overcurrent protection limits.

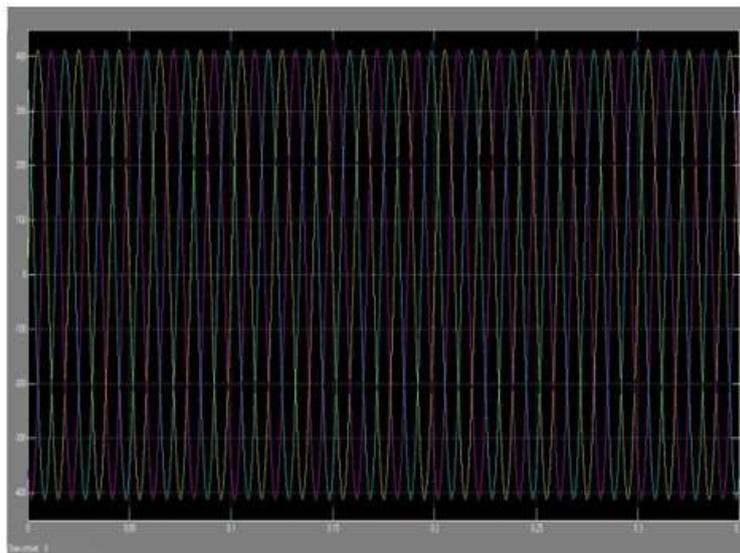
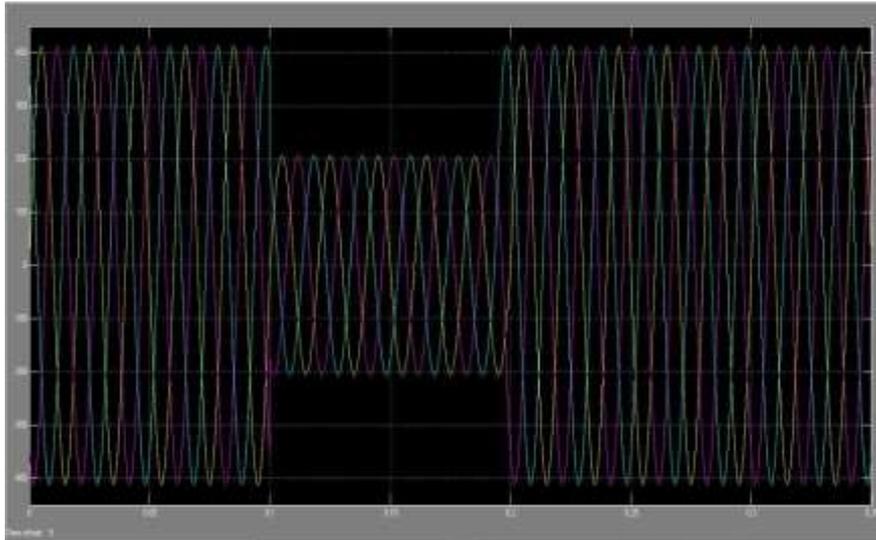
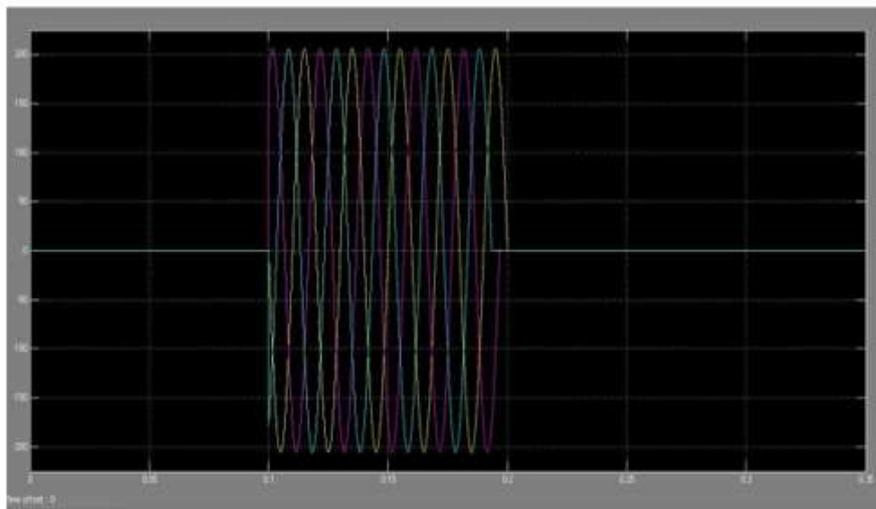


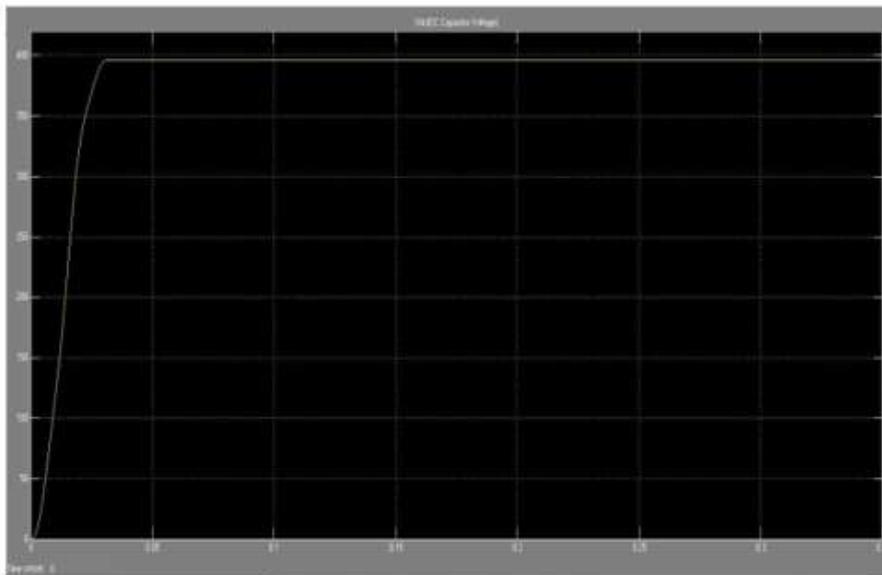
FIGURE 4 ZVSG Current while VFOC Control is hired for connecting to the grid



**FIGURE 5** A Pre-Synchronizing Control Method Is Hired to Decrease the Current Increment



**FIGURE 6** A pre-synchronizing the compensation three phase currents



**FIGURE 7** Dc- link voltage

### 4. Conclusion and Future work

The paper has explored the concept of multi-mode operation of an impedance-source virtual synchronous generator (ZVSG) with a single-stage Z-source inverter (ZSI), with a virtual synchronous generator control strategy and the ability to offer fundamental grid ancillary services. To overcome the shortcomings of phase-locked loops (PLLs) in conditions of harmonically distorted grid voltage a virtual flux-oriented control scheme is used to accurately determine the reference angle used in the Park transformation. The system performance has also been considered in case of islanded mode to grid connected mode, where a pre-synchronization control strategy is used to reduce the phase difference between the grid and the converter, which reduces the inrush current that occurs when connecting to the grid.

Moreover, there is an addition of grid-code-conformable reactive control mechanism of power to boost voltage support in the case of grid disturbances. When a voltage sag is detected, the control strategy switches from maximum power point (MPP) mode to low-voltage ride-through (LVRT) mode. This method keeps the individual current in the grid at a constant peak when using LVRT, to keep the converter well within its over-current limit. The applicability of the suggested ZVSG and its control scheme is tested using various case studies that were being implemented on an OPAL-RT real time digital simulator. The offered seamless control architecture allows the ways to make a transition between normal mode and fault condition smooth, which proves the robustness and relevance of the system.

**Acknowledgement:** Nil

### Conflicts of interest

The authors have no conflicts of interest to declare

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