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# PV Inverter with Decoupled Active and Reactive Power Control to Mitigate Grid Faults

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# PV Inverter with Decoupled Active and Reactive Power Control to Mitigate Grid Faults

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**Abstract**. Low power distributed Photovoltaic (PV) systems would be a dominant power generator in future grids. This PV penetration significantly influence the grid stability, especially in an event of grid faults. Traditional PV inverters disconnect themselves from grid on detecting a low voltage at their point of common coupling (PCC). A temporary low voltage grid fault can lead to outage, if PV inverters are not equipped with low voltage ride through (LVRT) feature. During a low voltage grid fault PV inverter can assist the grid recovery process by not only staying connected to grid but also injecting reactive power into the grid. Many grid code standards have issued guidelines to inject reactive power during a low voltage fault. Development of low voltage ride through inverters require decoupled power flow control. In addition to maximum power point operation and standardized current injection to the grid, modern PV inverters should be able to deal with LVRT and loss of grid (LoG) ride through features, as demanded by the regulating grid codes. Reduction in grid outages can be achieved, if the PV inverters stay connected during LVRT, LoG and short circuit faults. Most of previous studies on LVRT control of PV inverters have not short circuit faults and loss of grid faults at PCC. This work proposed a PV inverter controller capable of controlling complex power into the grid. A decoupled current regulator with feed forward compensation is modelled. A short circuit grid fault is also tested with the developed PV inverter. It is found that the PV inverter ride through the low voltage and short circuit faults. The system is simulated in MATLAB(Simulink), the designed controller can provide decoupled active and reactive power to the grid during the fault events.

## 1. Introduction

Conventionally a transient sag and swell of grid voltage is dealt centrally by a grid operator, usually at a power plant installation site, where reactive power (VAR) compensation is provided by a static compensation techniques (STATCOM) [1]. A large-scale passive capacitor/inductor arrangement can provide or absorb reactive power to stabilize the grid voltages where a single large power generator is supplying power to the grid. However, for the DG rich grid these solutions increase cost along with a demerit of slow dynamic response. They are not suitable to be installed at every low power DG. [2]. Recent raises concerns about grid reliability and stability[3]. As transient grid stability can no longer be controlled centrally by a grid operator, therefore reactive power support to the grid must be shared among all the DGs on the grid [4]. A transient fluctuation (Loss of Grid voltage) or Low voltage (Shortening of Grid Voltage), can result in long outages and overall grid failure. However, with a proper absorption or extraction of relevant reactive power during a transient event tends to prevent catastrophic grid failure[5]. In order to assist grid fault recovery, the right amount of active/reactive power should be injected by a grid tied inverter during the fault event[6]. Transient power flow can be controlled if the power references and the feedback power signals are readily available to the inverter controller [7]. Normally the inverter is working at MPPT and would insert the maximum rated current to the grid at unity power factor. An abrupt voltage dip or short circuit at the point of common coupling (PCC) would result in high current and low voltage [8]. Detecting this abnormal grid voltage, a traditional inverter would trigger an overcurrent protection and trigger a self-turnoff. If all the PV inverters on the grid behave in this way a power outage would happen. As the dominant power generating sources would have gone offline. Several minutes would be required to bring the grid online again.

On the other hand, a modern fault ride through enabled inverter would limit the output current while staying connected to the grid [9]. In another scenario a voltage fluctuation can cause temporary loss of grid for few cycles, the inverter will still sense zero volt at its PCC [10]. If the inverter is equipped with anti-islanding feature, eventually the inverter would turn off. A fault ride through inverter should discern a transient fluctuation and or islanding effectively. As modern grid evolved with majority of renewable distributed generators feeding the grid. It is necessary for inverters to ride through the transient fault event and stay connected for at least (150ms to 1.5s), as recommended by IEEE 1547 standard for connecting DGs to the grid [11]. An LVRT requirement defined by German grid codes is depicted in Figure 1 [12]. In addition to ride through feature, if an inverter provides reactive current to the grid during the transient event the grid may recover from the fault [11], thus preventing an overall grid outage and increases grid reliability. A decoupled active and reactive current reference generation and an analogous decoupled active and reactive controller would be needed to provide the grid fault ride through feature in PV inverters[1, 9]. A single-phase PV inverter is proposed in this work to provide fault ride through during the grid faults. Power decoupling and independent control of 'direct' and 'quadrature' components are the key features of the proposed inverter.

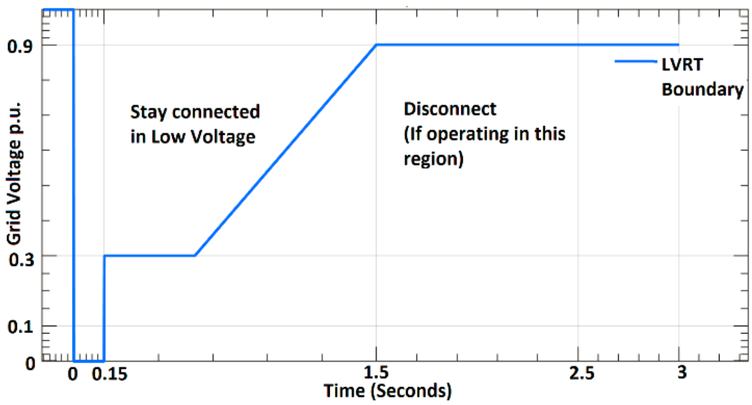


Figure 1. LVRT Grid Code Requirement

## 2. System Model

The block diagram in Figure 2 is used for system modelling. The system consists of PV string connected to transformerless inverter via DC-link capacitor. At the grid side H-bridge based MOSFET inverter is connected to an output L filter[13] and to the grid. An 'LCL' filter can also be utilized as it would reduce the filter size compared to 'L' filter. Voltage source grid tied inverter (VSI) can be represented by differential equation as:

$$v_{inv}(t) = Ri_{inv} + \frac{Ld}{dt}i_{inv} + v_g \quad (1)$$

Where $v_{inv} = u.\,Vdc$, is the inverter output voltage and 'u' is the modulation index, '$ig$' is the grid current supplied to the grid by the inverter and '$vg$'is the grid voltage. Equation (6) can be written in Laplace domain as:

$$\frac{i_{inv}(s)}{v_{inv}(s)-v_g(s)} = \frac{1}{R+sL} \qquad (2)$$

Where L=L1+L2, and 'R' is the series resistance. Equation (2) suggests that it is a single pole 1st order system.

## 3. Power Decoupling

It is mandatory for next generation inverters to provide decoupled active or reactive power to the grid during normal and low voltage mode [14]. PQ power theory for three phase electric systems suggests that the electric signals (Phase a, Phase b, Phase c) can be transformed into equivalent two dimensional orthogonal 'αβ' coordinate system with Clarke transform.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (3)$$

Given current in 'αβ' coordinate system, the instantaneous power can be written as:

$$\begin{bmatrix} P_i \\ Q_i \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (4)$$

Where '$P$' and '$Q_i$' is the instantaneous active and reactive power component respectively. In order to decouple the single phase active and reactive power we need orthogonal signal pair. Single phase system does not have orthogonal 'β' component, so the 'β' component is generated fictitiously. There are many methods to generate 'β' component. Amongst them the most commonly used method is 'T/4' delay method[15]. In this method an 'α' component is delayed by quarter of cycle to generate the 'β' component. Instantaneous and decoupled power components are calculated from Equation (5) and (6) [16]:

$$P = \frac{V_\alpha I_\alpha + V_\beta I_\beta}{2} \qquad (5)$$

$$Q = \frac{V_\alpha I_\alpha - V_\beta I_\beta}{2} \qquad (6)$$

Equations (5) and (6) suggests that once an orthogonal pair of grid voltage and current is obtained, it is possible to generate independent current references to control active and reactive power feed to the grid.

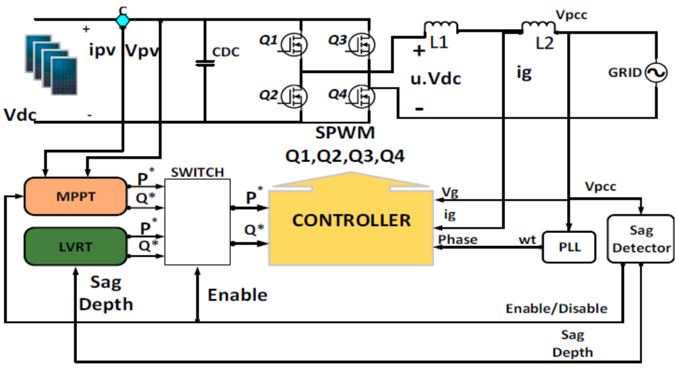


Figure 2. Transformerless PV Inverter

An overall PV system is depicted in Figure 2, the grid conditions are sensed by the controller and orthogonal signals are extracted by applying a 'T/4' delay-based algorithm on both current and voltage signals. Injected active and reactive power values are calculated according to Equation (4). The difference between injected and reference values are fed to the feed forward PI controller[17].

## 4. Controller Design

Three cascaded control loops are proposed to control PV inverter, an outer most voltage control loop, an intermediate power control loop and the innermost current control loop. PI controller is the simplest and the reliable choice with good tracking. However, variable AC quantities are needed to be converted into equivalent DC signals for acceptable steady state and transient performance [18]. Variable ac quantities (alpha, beta) in fixed reference frame can be converted to fixed quantities (direct, quadrature) in synchronously rotating reference frame as shown in Equation (7). In this way we can control of direct 'D' and quadrature 'Q' component of current independently [1]. DQ components can be obtained by Park transformation on orthogonal signals (αβ).

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad (7)$$

Where '$X$' and '$X_q$'are the DC equivalent signals of variable ac signals '$x_\alpha$'and '$x_\beta$' respectively. The obtained dc signals can be regulated with the conventional PI controller, with much improved steady state error. For the case of voltage source inverter, we need a reference voltage as a modulating signal for PWM generator. In order to decouple this reference signal, the direct and quadrature current components are feed forwarded as shown in Figure 3 [19]. The voltage loop controls the DC-link voltage, the input of this loop is the difference between the reference DC-link voltage and its sensed value represented in Equation (8). This loop generates the active power reference as shown in Equation (10) , which is an input of an intermediate power control loop[20]. Another input of this loop is reactive power reference, which is given by the user according to relevant grid codes. Kp and Ki values can be tuned with the SISO tool in MATLAB.

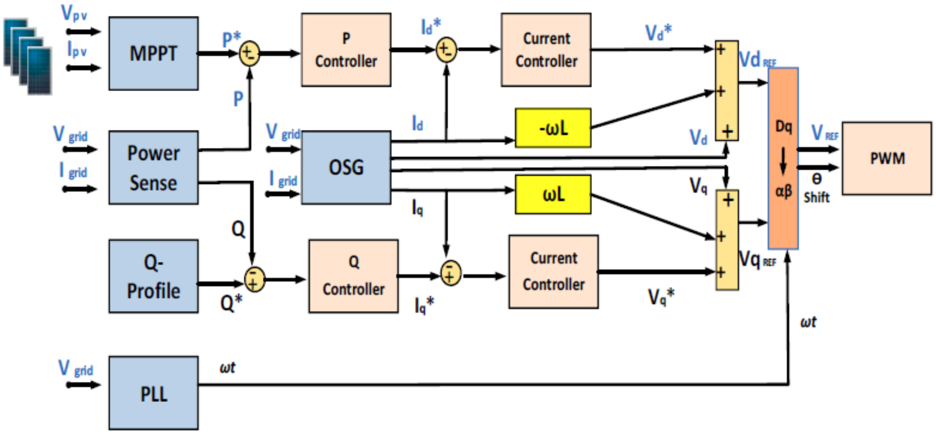


Figure 3. Controller Structure

$$e_v = e_{dc}^{\text{ref}} - V_{dc} \quad (8)$$

$$i_{ref} = k_p \cdot e_v + \frac{k_i}{s} \int e_v dt \quad (9)$$

$$P_{ref} = i_{ref} \cdot |v_g| \quad (10)$$

An intermediate power controller provides the decoupled current references in the form of direct and quadrature components. Now we need to sense the real time values of 'DQ' components, so that the error between the reference and the sensed quantities can be fed to the PI controller.

The 'Hall' sensors sense inverter current and grid voltage, these signals are delayed by quarter of a cycle to generate the 'β' component. Now'αβ' pair would be converted to synchronous 'dq' reference frame by using Equation 7, since phase angle '$\theta$' is already obtained by a PLL unit [16].

$$\begin{bmatrix} i_{d_{ref}} \\ i_{q_{ref}} \end{bmatrix} = \frac{1}{v_{gd}^2 + v_{gq}^2} \begin{bmatrix} v_{gd} & v_{gq} \\ v_{gq} & -v_{gd} \end{bmatrix} \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix} \quad (11)$$

$$i_{ref} = i_{d_{ref}} sin\omega t - i_{q_{ref}} cos\omega t \quad (12)$$

The calculated '$i_{dref}$'and '$i_{qre}$' controls the active and reactive power respectively[7]. The error signal between calculated current and the sensed current is regulated by a PI controller.

$$G(S) = K_p + \frac{K_i}{S} \quad (13)$$

PI controller is chosen because of its superior performance and ease of implementation. All four controllers in Figure 8 used PI controller with mathematical expression in Equation (13) where Kp is proportional gain and Ki is integral gain. A current reference is generated from above explained outer loop, and it would be fed to the inner loop. As a common practice, design of multi-loop nested control is carried from the inner most loop towards the outer loops. Therefore, the current loop must be addressed in the first place. The inner most loop senses the grid current and orthogonal signal generator (OSG) generates the 'dq' current components[21, 22]. An error between observed and reference signals is fed to the current controllers as shown in Figure 3. The output of current controllers is fed to PWM modulator to generate the gating pulses for an inverter's full bridge structure as shown in Figure 3. It can be seen that there are four controller and two decoupling blocks.

## 5. Simulation

A simulation of transformerless inverter with power decoupling is implemented in MATLAB Simulink as shown in Figure 6. SISO tool is used to tune the controller parameters. Table 1 shows the simulated PV inverter.

Table 1. Model Specifications

| *Description* | *Symbol* | *Value* |
|---|---|---|
| Inverter side filter inductor | $L_1$ | 3.5mH |
| Filter capacitor | $C$ | 2μF |
| Grid side filter inductor | $L_2$ | 50μH |
| Nominal grid voltage | $V_g$ | 240 V (rms) |
| Inverter dc link | $V_{dc}$ | 400 Vdc |
| Nominal grid frequency | $f_g$ | 50Hz |
| Nominal switching frequency | $f_{sw}$ | 3.8kHz |
| Nominal sampling frequency | $f_s$ | 400kHz |
| Nominal Power | $P$ | 1000W |

The inverter is started at 0W output power, at 0.2s the power reference is set to 100% active power and 0% reactive power. The inverter's PLL synchronize its output to the grid in 2 cycles. During these 2 cycles a transient reactive power flows to the grid. The inverter feeds active power to the grid as shown in Figure 4. On the grid voltage scale the grid current (Red) is superimposed and scaled by a factor of '20' in order to view the phase difference.

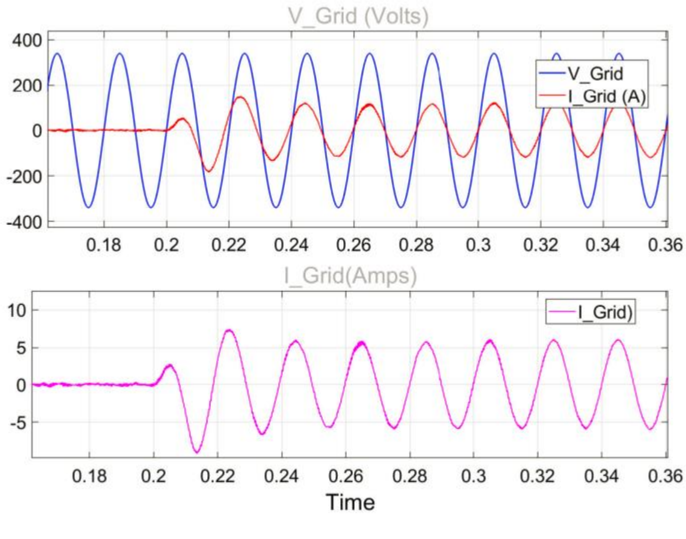


Figure 4. Normal Operation

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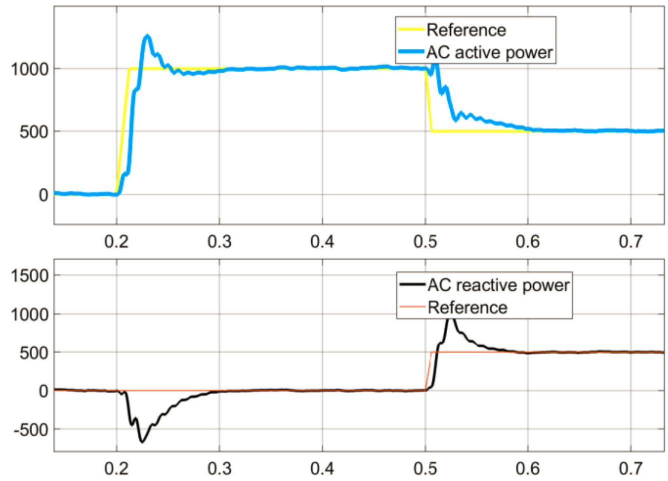


Figure 5. Active & Reactive Power Tracking

As shown in Figure 5, at 0.5s the power references are set as 50% active power and 50% as reactive power. Current is leading the voltage during a low voltage event as shown in Figure 7, thus providing the positive VARS. Figure 8 shows that the inverter follows both active (500 W) and reactive power (500VARs) references. At 1s active power has been set to 0% and reactive power to 100% (1000VARs), 90 degrees phase shift can be observed between injected grid voltage and current. At 2 Sec both active and reactive power set points are set to 0%. An overall result of the simulation setup in shown in Figure 8. The results show that by decoupling the active and reactive power and controlling it via direct and quadrature component approach provides good tracking performance.

This control approach can be utilized in modern PV systems which should be designed to provide reactive power to the grid in an event of fault. A low voltage grid fault of 50% is simulated to verify the ride through and current regulation of the control scheme. On detecting a sag, the active power is reduced and reactive power is supplied to the grid, thus low voltage ride through capability is implemented.

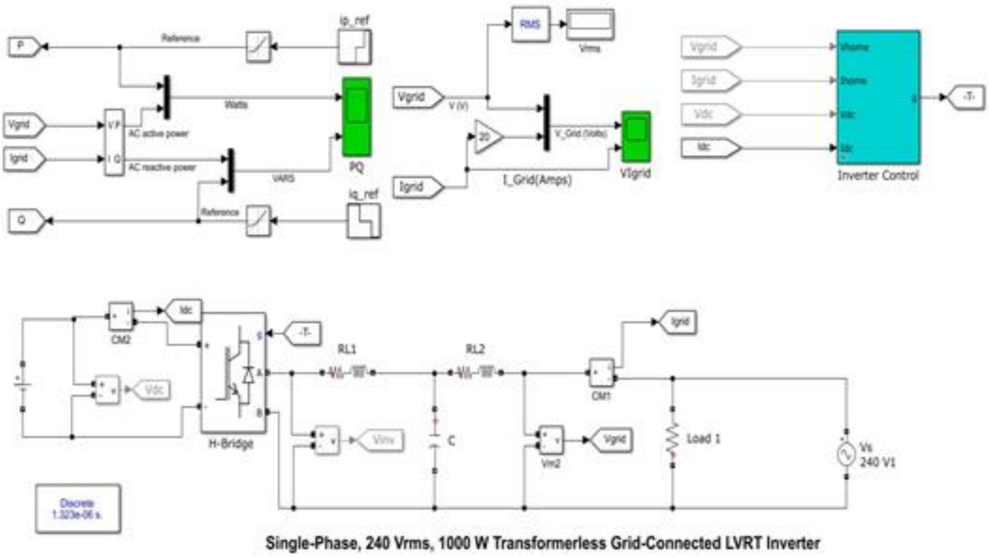


Figure 6. SIMULINK Model

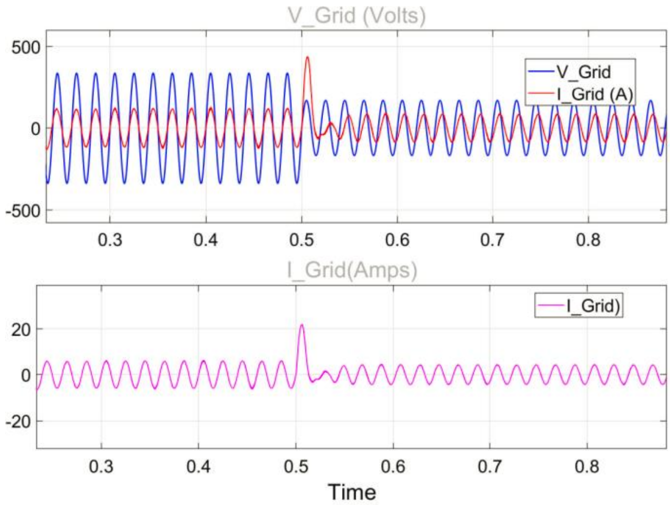


Figure 7. Low Voltage Ride Through Mode

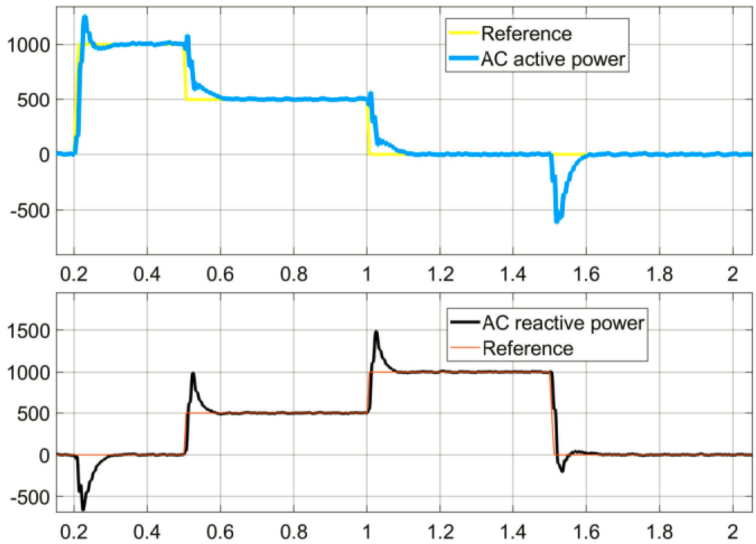


Figure 8. Complex Power Flow into Grid

A high current spike is observed on first cycle of sag occurrence. However, the current controller curtails the current and reduce the active power and increase the reactive power as shown in Figure 7. In another experiment a short circuit at the gird is also simulated. Here the controller still limits the current but initial high current spike could be dangerous as it would induce very high rate of change of current (di/dt), as shown in Figure 9. The MOSFET switches must be capable to deal with this high in rush current. Modern PV inverters should stay connected to the grid during voltage sags (shortening of grid voltage) and fluctuations (loss of grid voltage). Further research would be carried out to make PV inverter more resilient to these grid faults.

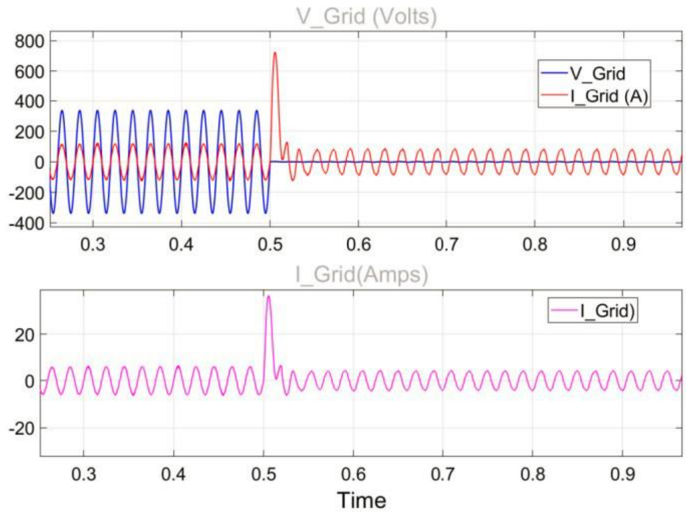


Figure 9. Zero Voltage Ride Through Mode

During both of these scenarios the active power injection to the grid would be zero, however, limited amount of current should still be injected into the grid so that the grid may be assisted in recovering from fault. The performance of current controller, sag detector, synchronization unit (PLL) must be deeply analysed to develop the grid faults resilient PV system, these systems would be explored in the future research.

## 6. Conclusion

In this work, a 1kW single-phase grid connected PV inverter with LVRT capability is designed and analysed. The main objective is to control active and reactive power independently in an event of grid fault. A grid connected inverter is modelled and a single-phase PQ control strategy is adopted to decouple the injected power into direct and quadrature (DQ) components. Once the DQ current components are available the active and reactive power is controlled by using PI controller with feed forward control. Result shows decoupled control of active and reactive current can be effective in providing reactive power to the grid during transient fault event. 50% and 100% grid voltage sag has been tested on the designed controller, which successfully limits the current and fulfils the low voltage ride through criteria.

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