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Fault Ride Through of a Grid-connected PV System with Quasi Z source Inverter

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Abstract: This paper presents fault ride through (FRT) schemes for a three phase Quasi Z source single stage PV inverter (QZSI) that is connected to the grid after distribution network. The QZSI inverter employs a unique LC network to couple the inverter main circuit to the input of the PV panel. By controlling the shoot-through duty cycle, the QZSI can theoretically produce any desired output ac voltage, even greater than the line voltage. In this paper, three different control strategies to improve the low voltage ride through capability are proposed when there is voltage sag from the grid side, so that the grid fault ride through requirements can be fulfilled. Scheme A involves control modification in the system, on the other hand, Scheme B and Scheme C involves hardware modification in the circuit topology by adding chopper circuit across the DC link in scheme B and across the QZSI capacitor in scheme C. A comparative study among different control schemes are carried out to see the effectiveness of the control schemes under different types of symmetrical and unsymmetrical fault conditions. Observations based on comparing simulations and recommendations are reported.

1. Introduction

Power quality has become a major concern during the last decades. Voltage sag is considered the most important and commonly occurring power quality issue. It is defined as a short and instantaneous decrease in the nominal voltage, where the decrease is in the range of 10%–90% of the nominal voltage for a duration in the order of 0.5 cycles up to a minute [1]-[3]. Power quality is a concern for utility and grid operators due to a large penetration of intermittent and stochastic renewable power generation sources such as PV, wind, biomass, etc. One of the major concerns when designing and controlling grid tied PV inverters is meeting the grid requirements. International grid requirements demand low voltage ride through capability (LVRT) and maintaining the grid functionality during fault conditions [4],[5]

There are a lot of power converter topologies employed in PV systems; they are characterized by two-stage or single-stage, with transformer or transformerless, and with two level or multilevel inverter [6]. Single stage transformerless power converters are attracting more attention because of higher efficiency, smaller size and less cost. The newly invented Quasi Z source inverter (QZSI) has the unique feature of boosting the voltage and converting to AC in a single stage by introducing the shoot-through operation mode, which is forbidden in the traditional voltage source inverters [6]-[14]. The QZSI has proven its efficiency in many PV system applications [9]-[13]. The structure and operating principle [11], steady-state analysis [12], modulation methods [13], and dynamic modelling and analysis of QZSI have been studied in details.

Any voltage sag either on the PV side or the grid side will affect the DC link voltage. During voltage sag on the grid side the DC link voltage will increase due to the power imbalance between the PV and grid sides. This, sudden DC link voltage increase will lead to an inverter trip unless additional devices are installed or the control scheme is modified to mitigate the excess DC link voltage on the inverter above the rated designed value [14]. Any interruption in the system will cause costly down time and several other problems from the end user and grid operator viewpoints, especially when the PV penetration level is increasing significantly [16]-[22]. Thus, concerns about this problem have reasonably increased and many studies about voltage ride through without shutting down the system have been carried out.

There exist only a few studies in power system literatures which discusses the voltage sag, fault ride through features of grid tied or standalone QZSI used in different applications including the PV system [23]-[28]. Z source inverter can provide voltage ride through capability during voltage sag on the DC link voltage. However, the effect of voltage sag at the AC grid side resulting from either a symmetrical or non-symmetrical fault is not studied. This study is important and hence an attempt is made to augment the FRT capabilities for the grid tied QZSI based photovoltaic system, in this work.

Existing voltage ride-through solutions include either change in the system topology or modification in the control scheme. Modifications to the system topology involve the use of a DC link brake chopper circuit [29]. The use of an energy storage option might be another solution to this problem for grid tied PV inverter, which hasalready been tested to other renewable energy applications[30]-[32]. Modification of the control scheme is needed when operating at fault conditions as reported in a QZSI based adjustable speed drive application [27]. In the case of a PV system under normal operation, the maximum power should be extracted from the PV panel and delivered to the grid. However, under fault operation the controller must react to mitigate the excess DC link voltage depending on the depth of the voltage sag. So the active and reactive reference power should be recalculated according to the voltage sag depth.

In this paper, three different schemes are proposed to augment the FRT capability of QZSI based grid tied PV system. One scheme (A) includes control modification where the active power reference will be recalculated depending on the voltage dip due to the fault at grid side. Two other schemes (B and C) involve circuit topology modification where a DC chopper circuit is added across the inverter in scheme B or across one of the QZSI capacitors in scheme C. The effectiveness of each scheme is tested under different types of symmetrical and unsymmetrical fault scenarios. The objective is to find a cost effective solution to the FRT problems of QZSI based grid-tied inverter.

The paper is organized as follow: section II gives a brief analysis about the Quasi Z- Source inverter topology. The control scheme is explained in section III. Simulation results of fault operation using three different schemes are discussed in section IV.Finally, conclusions are presented in section V.

2. Quasi Z-source Inverter Circuit Topology

The topology of voltage fed Quasi Z source inverter used in grid-connected mode is shown in Fig. 1(a). The equivalent circuit of the QZSI in the shoot through mode and non-shoot-through mode is shown in Fig. 1(b) and Fig. 1(c) respectively. The equivalent circuit of QZSI is given in Fig. 1 (b) and fig.1 (c) from which it can be seen that the operation of QZSI is divided into two main modes: the shoot-through mode and the non-shoot through mode (active mode). During the non-shoot through mode the inverter is operated using the normal sine PWM technique like a conventional voltage source inverter. While, in the shoot-through mode a short circuit in the DC link is created, which is prohibited in the traditional voltage source inverter.

Dependent on the duration of the shoot-through the DC link voltage will be boosted to a value higher than the input voltage, and therefore boosting the DC link voltage without using additional boost circuit.

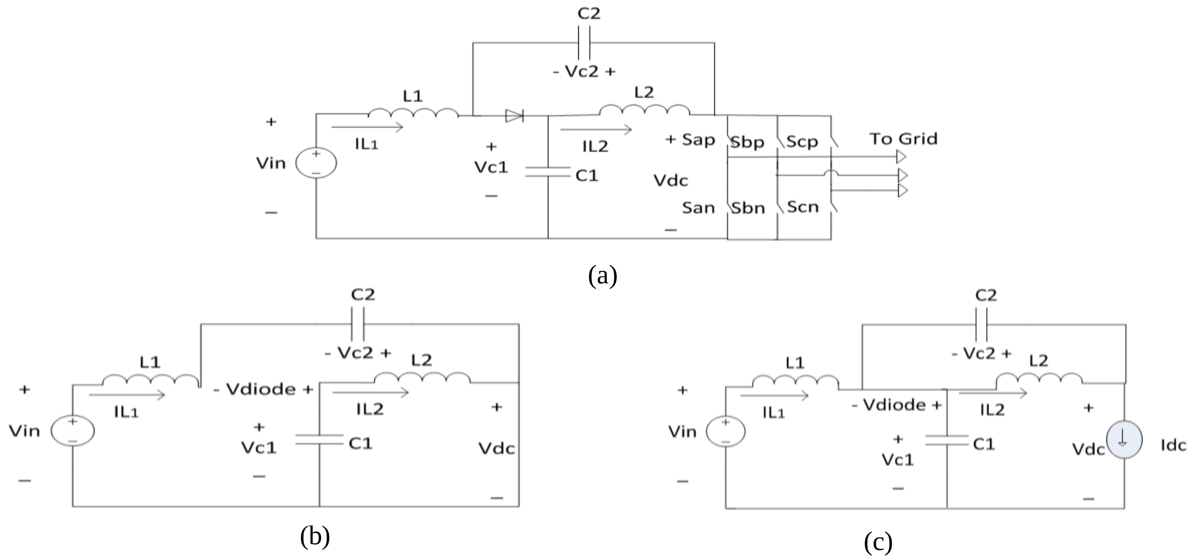


Fig. 1. Voltage fed QZS inverter (a) Topology (b) Shoot-through mode (c) non-shoot-through mode.

The operating principle described control of the Quasi Z-source inverter have been detailed in [7].

The average values of the capacitor voltages V_{c1} and V_{c2} in Z source network are given as follows:

$$V_{c1} = \frac{1-D}{1-2D} V_{in} \qquad (1)$$

$$V_{c2} = \frac{D}{1-2D} V_{in} \qquad (2)$$

where V_{in} is the DC input voltage, D is the shoot-through duty cycle, which is defined as $\frac{T_{sh}}{T}$, T is the switching cycle and T_{sh} is the shoot through time interval over a switching cycle [2].

The relationship of the DC link voltage V_{dc} and the DC input voltage is given in (3):

$$V_{dc} = \frac{1}{1-2D} V_{in} = BV_{in} \qquad (3)$$

where B is the boost factor resulting from the shoot-through state.

Thus, the peak value of the AC side voltage is given by (4):

$$v_{ac} = MB\frac{V_{in}}{2} \qquad (4)$$

where M is the inverter modulation index.

$$\frac{1}{1-2D} = B \qquad (5)$$

Hence, there are two parameters needed to be controlled in order to get the desired output AC Voltage. The modulation index M which exists in the traditional VSI, and the boost factor B which is determined by the shoot-through time.

Many modulation techniques were proposed in the literature, such as simple boost control [6], maximum boost control [7], and maximum constant boost control [8]. The simple boost control shown in Fig. 2 is adopted in this paper due to its simplicity as the focus of this study is not to develop new modulation technique for Quasi Z source inverter. In the mentioned method there are two more modulation references v_P^* *and* v_N^*, which are equal to or greater than the peak value of the three phase voltages, besides the existing three references $v_a^*,\ v_b^* and v_c^*$.

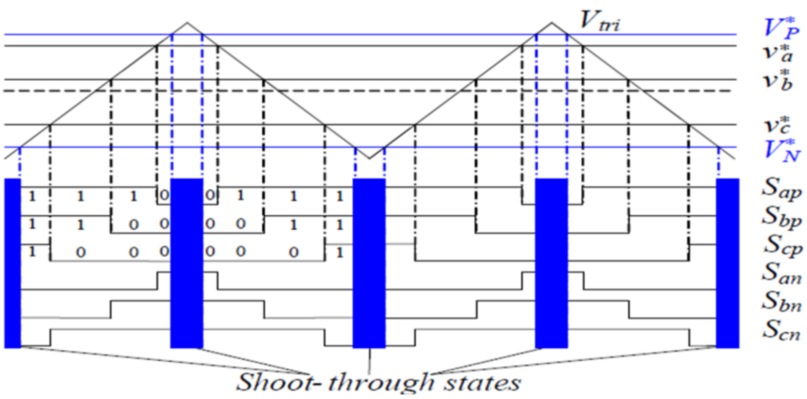


Fig. 2. Simple boost control for QZSI

3. System Modelling and Control Strategies

Figure 3 shows the system model and the control schemes of three phase Z source inverter used in grid-connected PV system. The three phase PV system is connected to the grid via a transformer and a distribution line. The control scheme should be able to 1) deliver the maximum power (MPPT) from the PV system 2) regulate the inverter DC link voltage 3) maintain the grid voltage at the desired level set by utility operator and 4) provide voltage ride through capability and maintain the DC link voltage within the acceptable limits when the voltage sag occurs due to either symmetrical or non-symmetrical faults.

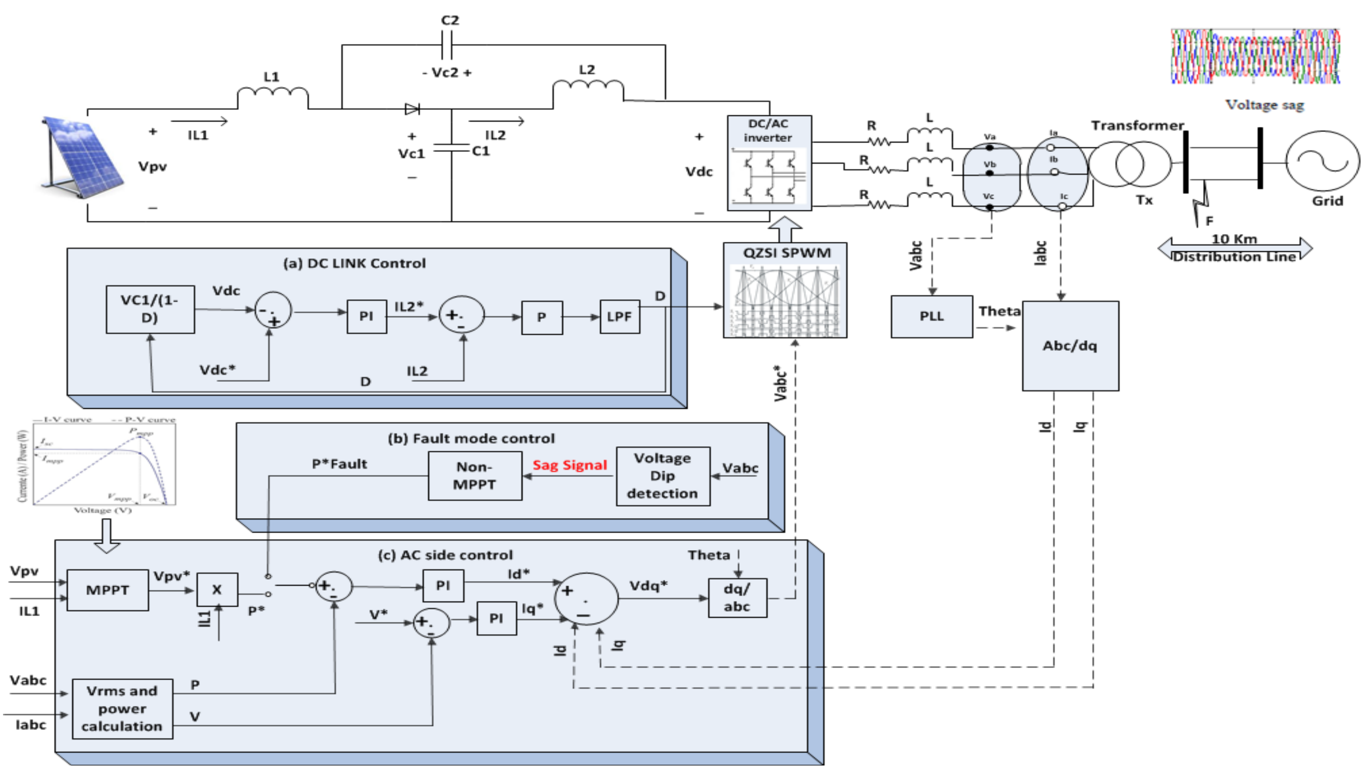


Fig. 3. System model including main circuit, modulation and control

3.1. PV Modeling

Figure 4 shows the equivalent circuit of PV panel. A PV array can be described by its current – voltage characteristic function as givenin Eq. 6 and Eq. 7 [36].

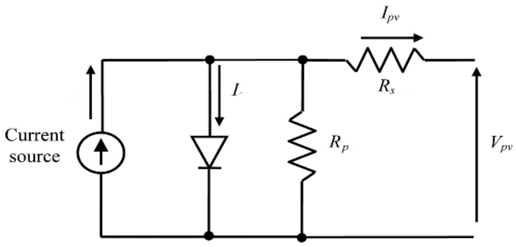


Fig. 4. Equivalent circuit of a PV module

$$I_{pv} = N_p I_{pv} - N_p I_o \left[\exp \frac{q(V + IR_s)}{N_m N_s KaT} - 1 \right] - \frac{V + IR_s}{Rp} \quad (6)$$

$$I_o = \frac{N_p I_{scn} + K_i \Delta T}{\exp\left(q \frac{(N_m V_{ocn} + k_v \Delta T)}{N_m N_s akT}\right) - 1)} \quad (7)$$

where I_{pv} and I_o are the photo-current and reverse saturation current of the PV module respectively. $N_s$andN_p are the number of series and parallel connected cells , q is the electron charge (1.602176×10- 19 C), k is the Boltzmann constant (1.3806503×10-23 J/K) and a is the ideality factor of the diode. $R_s$andR_p are the equivalent series and parallel resistances of the module respectively.

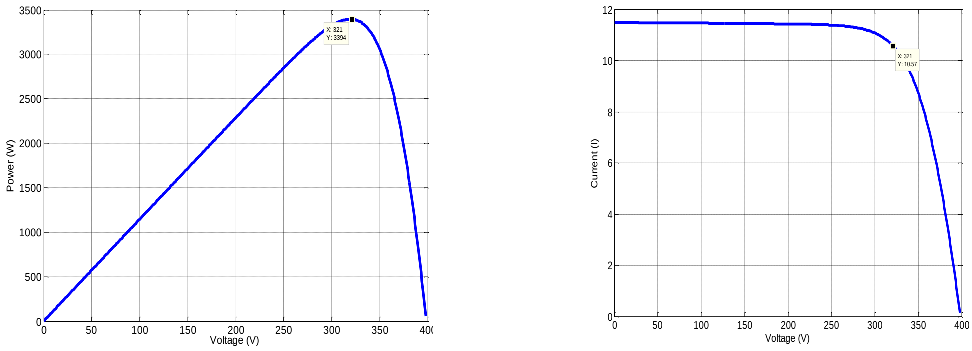
3.2. MPPT Control

The maximum power of the PV panel at specific temperature and irradiation may be extracted using the fractional open circuit voltage technique [32][33]. The voltage of a PV module at maximum power point (VMPP) has nearly a linear relationship with its open circuit voltage (VOC). The relationship can be written as

$$v_{mpp} = K_{mpp} . v_{oc} \quad (8)$$

where K_{mpp} is a proportionality constant.

Figure 5 shows the voltage and power characteristic and the voltage and current characteristics of the input at the PV panel.



(a)(b)

Fig. 5.PV panel characteristics (a) Voltage and power (b) Voltage and current

3.3.DC link control

The QZSI utilizes the shoot-through duty ratio (D) to boost the DC link voltage. In the DC boost control loop shown in Fig. 3, the voltage across the DC link of the Z-source network is regulated. There are two control loops, inner current loop and outer voltage loop. The inner loop is used to control the inductor current, IL2 where its reference signal is given by the outer loop. The outer loop is used to maintain the DC link voltage across the Quasi Z-source network, V_{dc}. In the outer loop, the DC link voltage is compared to the DC link reference voltage signal, V_{dc}*. The error of these two signals is fed to the PI controller to create the current reference of the inner loop. The error of the current difference is fed through the proportional gain of the inner loop to produce the reference signal of the shoot-through states. To avoid the effect of shoot-through states on the active states, the shoot-through reference signal should be restricted according to the possible input voltage and the required output voltage. Finally, the output of the boost control is sent to the PWM modulator to generate the shoot-through duty ratio.

3.4.AC output control

For grid-connected operation, the real power is regulated using Id and the reactive power calculated from the voltage is regulated using Iq as verified in Eq. 9-11. The equations of the grid inverter can be given in a d-q frame rotating at the line frequency.

$$\frac{di_d}{dt} = -\frac{R}{L}i_d + \frac{v_d}{L} - \frac{v_{gd}}{L} + \omega i_q \quad (9)$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q + \frac{v_q}{L} - \frac{v_{gq}}{L} - \omega i_d \quad (10)$$

$$\frac{dv_{dc}}{dt} = -\frac{3}{2}\left(\frac{v_{gd}i_d}{Cv_{dc}} + \frac{v_{gq}i_q}{Cv_{dc}}\right) \quad (11)$$

Where, i_d and $i_q$are the direct and quadrature components of the inverter current, v_d and v_q are the direct and quadrature components of the inverter voltage, and v_{gd} and $v_{gq}$are the direct and quadrature components of the grid voltage. When controlling P and Q independently, v_d* and v_q* will be obtained. They are converted to stationary reference frame using the transformation (dq/abc) and SPWM signals are then generated accordingly. Control parameters of the system model are shown in Table 1.

Table 1: Control parameters

Power control	Voltage control	Current Control (Id)	Current control (Iq)
Ki = 200	Ki = 1	Ki=0.0001	Ki=15
Kp = 0.1	Kp = 0.1	Kp=0.2	Kp=0.1

3.5.Proposed Fault Ride Through Schemes

Any voltage sag on the grid will affect the DC link voltage of the QZSI which is located between PV and distribution transformer. During the voltage sag the DC link voltage will increase due to the power imbalance between the PV and the grid sides. In order to protect the system and maintain the DC link voltage in an acceptable range three different schemes (A, B, and C) are proposed as explained below.

Scheme A: In this scheme, the control scheme used in normal operation is modified, considering the fact that the system level cost should be remained the same. In normal operation, the PV system operates in MPPT mode. Once the grid voltage sag is detected, the PV array will switch to Non-MPPT operation mode and recalculate the appropriate active power according to the depth of the voltage sag in order to keep the power balance of the system. Scheme A is shown in Fig. 6(a).

Scheme B: Use of a DC chopper circuit across the DC-link capacitor is an approach, which has been used to protect conventional inverter from overvoltage during low voltage sag. In this work, a similar approach is proposed for the Quasi Z Source Inverter, where the braking chopper is placed across the DC-link to keep the voltage stress within an acceptable range. This scheme is shown in Fig. 6(b). The brake resistor R1 must be sufficiently rated to absorb the excess voltage and protect the DC link. The brake resistor will be calculated according to Eq.12

$$R = \frac{{v_{dc}}^2}{P} \qquad (12)$$

where P is the input power at the PV panel

Scheme C: The idea behind this scheme is to reduce the system cost compared to scheme B without compromising much the fault ride through performance. In this scheme which is shown in Fig. 6(c), the braking chopper is proposed to be applied across the capacitor C2, where the voltage is much lower than the DC-link voltage. In this case, the voltage stress across the switching module is much smaller than Scheme B. The braking resistor should be calculated according to Eq.13

$$R = \frac{{v_{c2}}^2}{P} \qquad (13)$$

where P is the input power at the PV panel

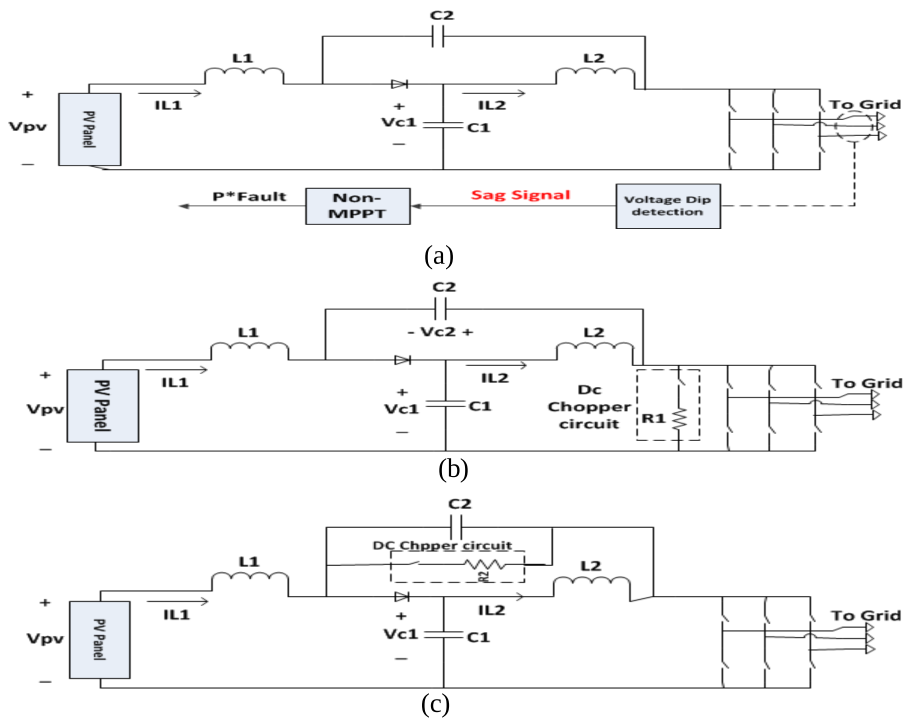


Fig. 6. Three different FRT methods (a) scheme A(b) scheme B (c) scheme C

4. Simulation Results

Simulations using Matlab/Simulink software was carried on to verify the three proposed FRT schemes of the grid connected QZSI based PV system. The system model shown in Fig.3 was simulated by adopting the illustrated control scheme and the FRT scheme shown in Fig. 6. Table 2 shows the used simulation parameters. To verify the FRT performance of QZSI for grid connected PV application the German grid code shown in Fig. 7 is taken as a reference. The FTR performance of the proposed control schemes are demonstrated using both symmetrical and unsymmetrical fault conditions. A 100 ms fault is considered to occur at 0.2 s on fault point ‘F’ (immediate after the transformer) of Fig. 3.

Table 2 Simulation parameters

PV power	3394 W	**R**	0.1 Ω
V_{mpp}	312 V	**L**	5 mH
I_{mpp}	10.6 A	**Tx ratio**	230/22 kV
L_1=L_2	0.5mH	**Tx leakage inductance**	0.029694 pu

C_1=C_2	300 µF	**Tx resistance**	0.006667 pu
V_{dc}^*	400 V	**Grid Voltage**	22 kV

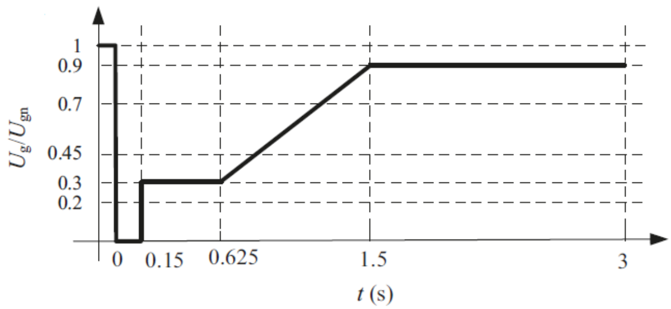


Fig. 7. Voltage fault ride through waveform.

4.1.Symmetrical Fault

The results using three different proposed control schemes when symmetrical three-line-to-ground (3LG) fault is applied are demonstrated below:

1) *Scheme A*

When the voltage sag is detected at the high voltage side of the transformer, the controller should switch from the MPPT mode while delivering the needed power to the non-MPPT mode by delivering power according to the depth of the voltage sag as shown in Fig. 3. Figure8-I shows the simulation waveforms for scheme A. The voltage sag is the result of the symmetrical 3LG fault occurred in the distribution line. It can be noted from Fig. 8-I-b that the DC link voltage will exceed about 75% from the rated value during the fault, further the controller was able to return back the voltage very quickly as shown in Fig. 8-I-c, once the fault is cleared, which is compliance with grid code requirement. The grid currents are also within an acceptable range as shown in Fig. 8-I-e.A shoot-through value will go to zero in the presence of voltage sag as shown in Fig. 8-I-f and the reference active power will be recalculated as shown in Fig. 8-I-g.

2) *Scheme B*

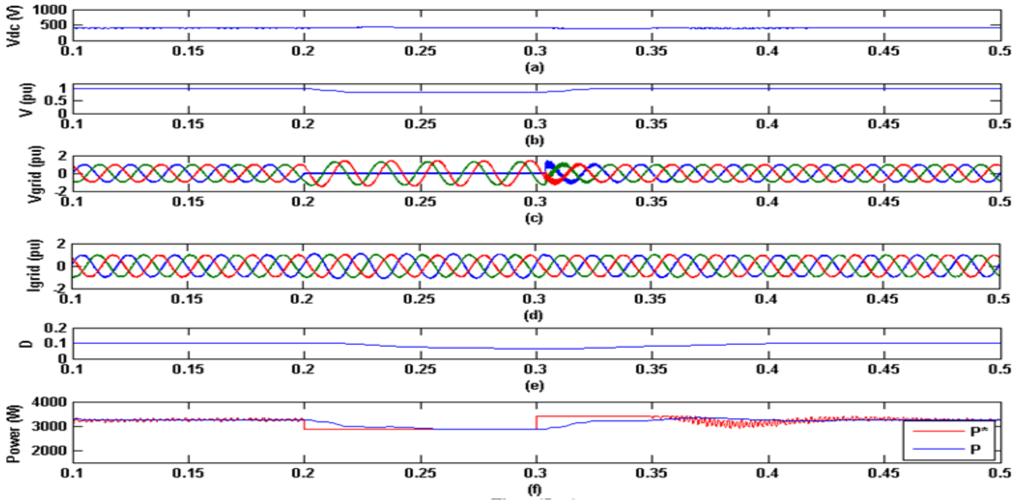
In this case, the DC chopper resistance is calculated according to Eq.12 considering rated DC link voltage (400 V) and rated power which gives the braking resistor value, R1 shown in Fig. 6(b) equals 47Ω. The responses obtained using scheme B is shown in Fig. 8-II. The FRT requirement is fulfilled and DC link voltage is kept within 25% from the rated value.

3) Scheme C

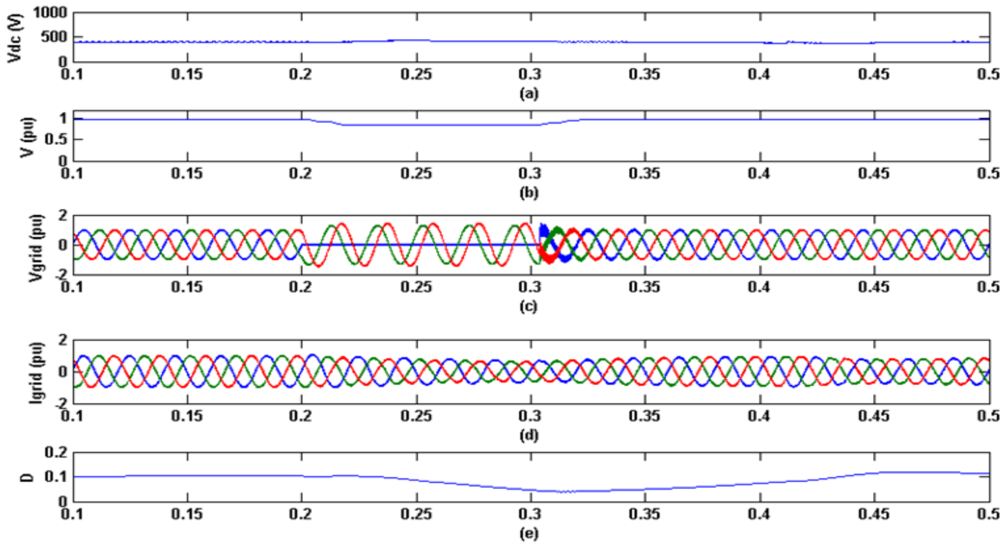
In this scheme, the Dc chopper will be placed across C2 in the QZSI configuration as shown in Fig.6 (c). Resistance value R2is equal to 3Ω which is calculated using 70V and 50% of rated power. The responses using this scheme are shown in Fig. 8-III. In this case also the FRT requirement is fulfilled and DC link voltage is kept within 12.5% of its rated value.

4.2. Unsymmetrical faults

The simulation results of the three different proposed methods when unsymmetrical two line to ground (2LG), single line to ground (1LG), and line to line (LL) faults are applied and are shown as follows in Fig. 9- Fig. 11. It can be observed that the proposed scheme C is the most effective method in suppressing the excess DC link voltage when different unsymmetrical faults occur.



(I)



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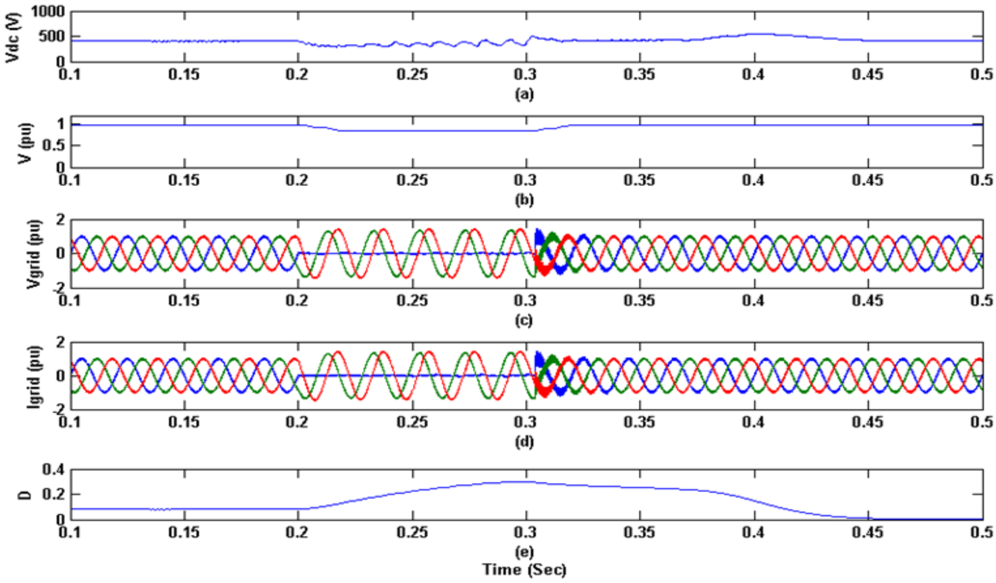


(III)

Fig. 8. Simulation of QZSI voltage sag under symmetrical fault conditions using (I) scheme A (II) scheme B (III) scheme C (a) DC link voltage (b) Filtered DC link voltage (c) Voltage sag (d) V_{grid} (e) I_{grid} (f) Shoot through (g) power.

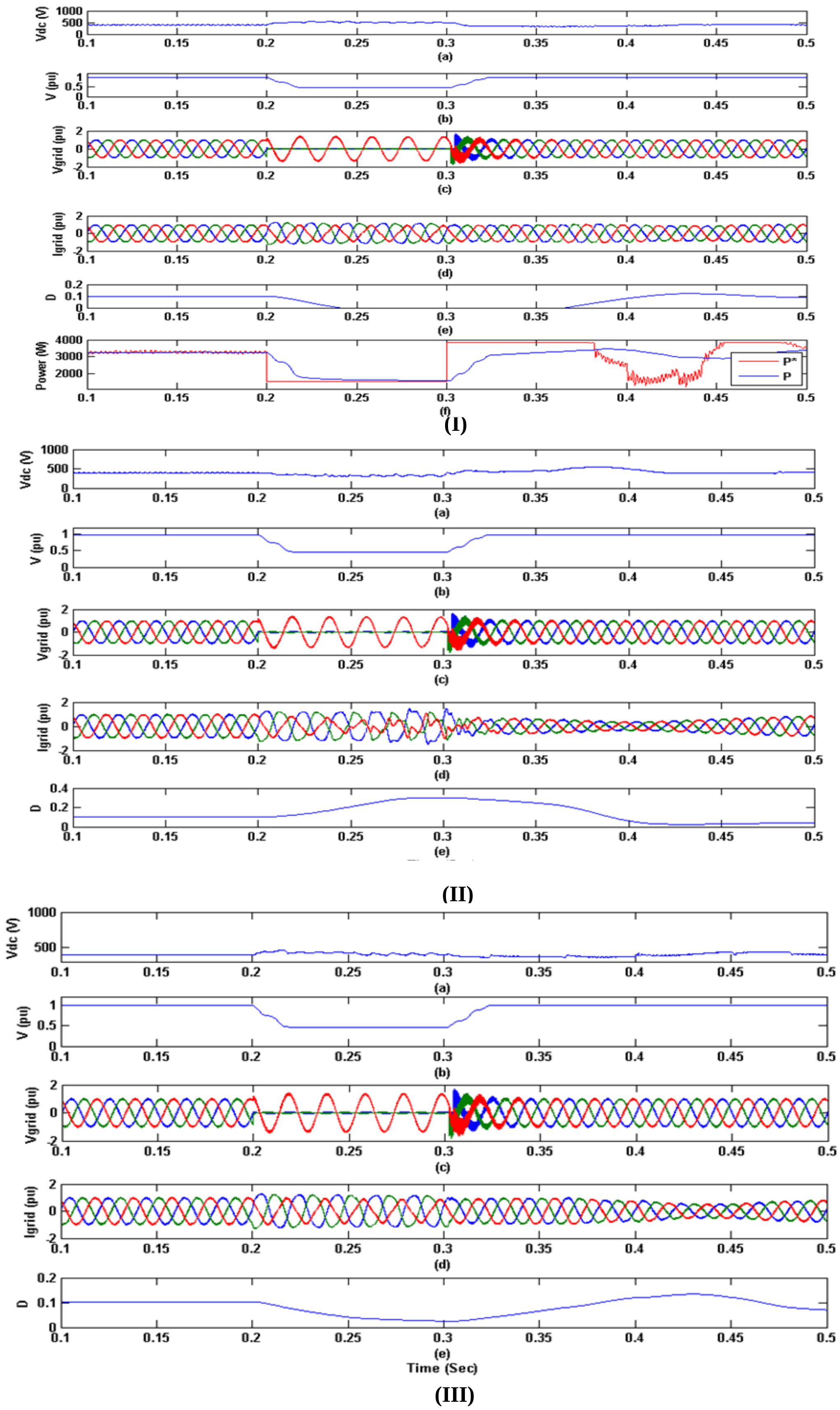
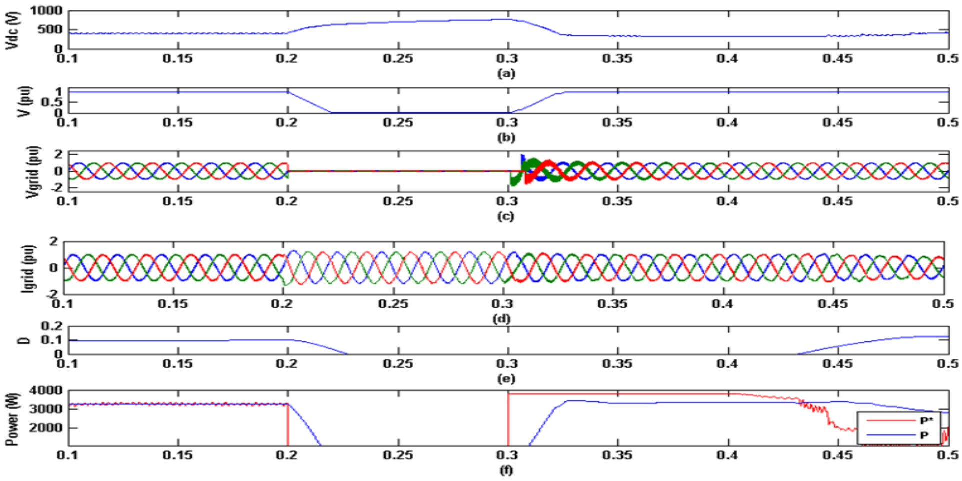


Fig. 9. Simulation of QZSI voltage sag under unsymmetrical (2LG) fault conditions using (I) scheme A (II) scheme B (III) scheme C (a) DC link voltage (b) Filtered DC link voltage (c) Voltage sag (d) V_{grid} (e) I_{grid} (f) Shoot through (g) power.



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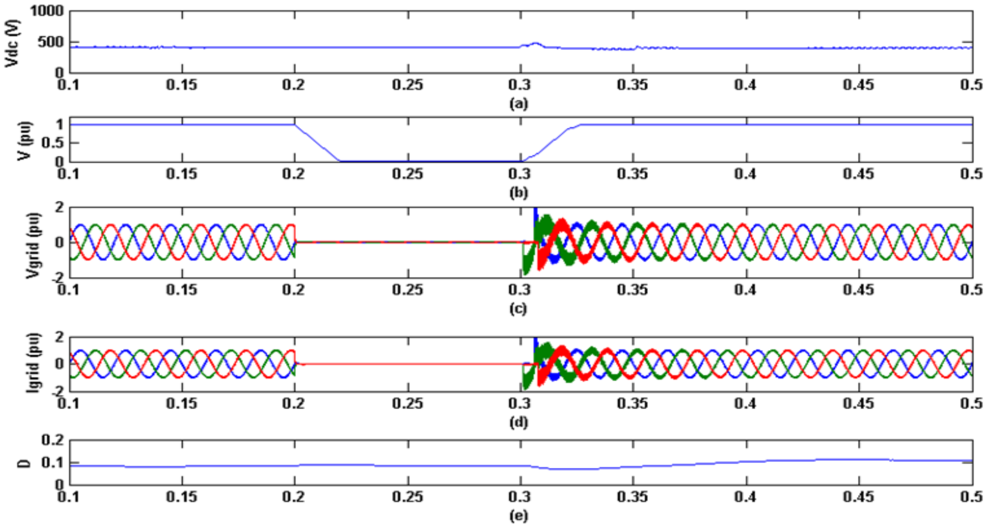

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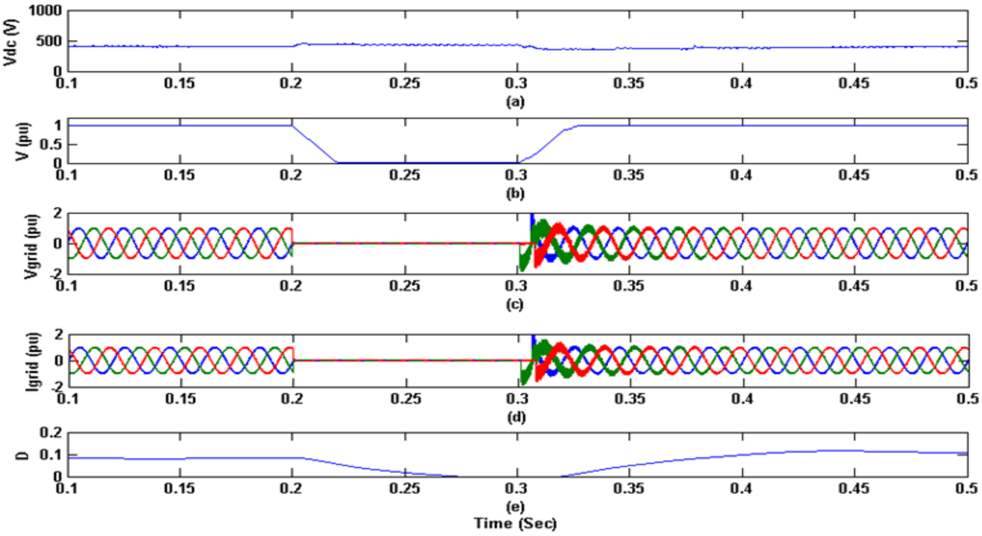
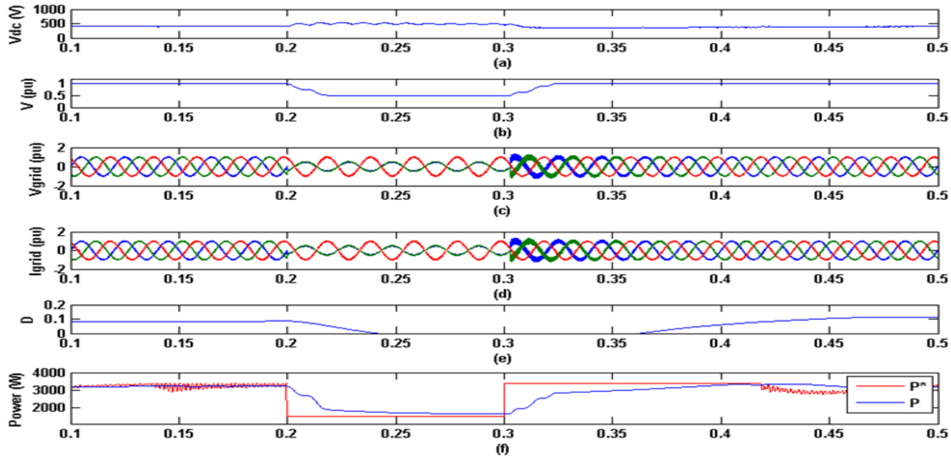


(III)

Fig. 10. Simulation of QZSI voltage sag under unsymmetrical (1LG) fault conditions using (I) scheme A (II) scheme B (III) scheme C (a) DC link voltage (b) Filtered DC link voltage (c) Voltage sag (d) V_{grid} (e) I_{grid} (f) Shoot through (g) power.



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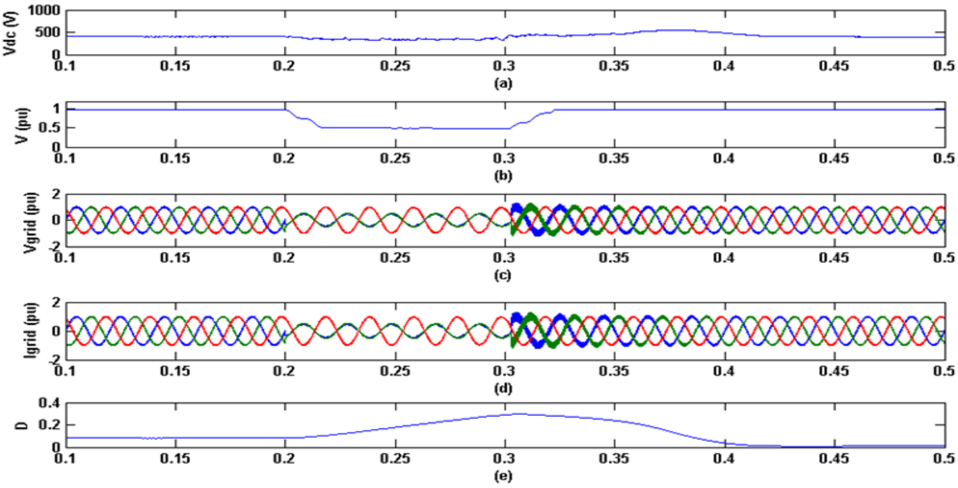

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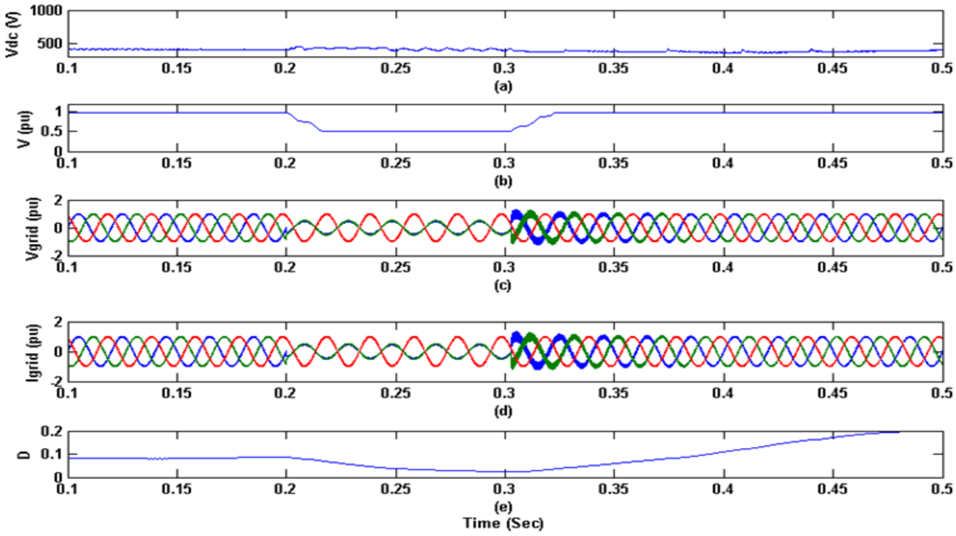

(III)

Fig. 11. Simulation of QZSI voltage sag under unsymmetrical (LL) fault conditions using (I) scheme A (II) scheme B (III) scheme C (a) DC link voltage (b) Filtered DC link voltage (c) Voltage sag (d) V_{grid} (e) I_{grid} (f) Shoot through (g) power.

5. Conclusion

In this paper different FRT schemes for QZSI based grid-connected PV system are presented. Three different control schemes are proposed as an attempt to find a cost-effective solution to maintain the FRT requirement of the PV system, when QZSI is used to connect the PV system to the grid. To verify the effectiveness of the control scheme the results are compared with realistic grid codes. The conclusion and recommendations are summarized as follows:

Scheme A is easy to implement and do not further increase the system cost as no additional hardware is required. Only the control modifications is required, which can give excellent FRT performance under both symmetrical and unsymmetrical fault conditions. However, the DC link voltage exceeds 50% of the rated value which might not be acceptable for longer fault duration, especially for the permanent fault condition.

Scheme B shows excellent FRT performance and also maintains DC link voltage within 25% of the rated value. The scheme causes additional cost for the braking chopper circuit.

Scheme C is found to an ideal and cost-effective solution as braking chopper is installed only across the capacitor where voltage stress is 12.5% of the rated DC link voltage. It is found that designing the braking resistance at 50% of the rated power of the PV panel is sufficient to keep the DC-link voltage variation within 12.5% from the rated value. Hence, Scheme C is recommended as the best fault ride through solution for QZSI based grid-connected PV system.

6. Acknowledgement

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