Chapter 7

Simulation of DFIG with Decoupled Control for Improved LVRT Response

7.1 Introduction

The Fault Ride Through capability of WTG is an important aspect of Wind Power. How effectively any WTG survive the fault shows its suitability and stability.

During fault on the system, the response of WTG is essential to ride through the fault successfully and maintain the stability. Low Voltage Ride Through (LVRT) is one of the most stringent requirement to be met by WTG. During the fault, i.e. voltage dips, there will be a mismatch between power generated and power delivered to the grid. Low Voltage Ride Through (LVRT) requirement mandates the ability of WTG to effectively manage the mismatch of power. In this chapter, the grid code requirement has been discussed. All prevailing grid codes demand that the WTG must remain connected to the grid during fault period. Not only this, but it should also deliver reactive power to the grid to support the grid voltage. Voltage dip or sag is one of the most adverse power quality issue [367]. The response of WTG should be evaluated and analysed.

The fault can cause temporary voltage rise/dip or a complete loss of voltage (interruption) depending on the severity of fault, fault locations and the system conditions. The protection technologies and fault characteristics dictates the duration and magnitude of the fault; whereas, the rate of the recovery likely to depend on the strength of the interconnection and reactive power support. The quantity of reactive power to be fed to the grid depends on the magnitude of grid voltage reduction during the dip and the system rated current capacity.

As the share of wind power increases, there will be a risk of simultaneous outage of significant part of the generating unit during fault condition. It will have profound negative effect on the power system stability. As the wind power contribution to the total load increases, it is required that they must remain connected to the grid and stay operating during fault condition to provide reactive power support to the grid under voltage dip condition. Such requirement is known as Fault Ride Through (FRT) or Low Voltage Ride Through (LVRT). The LVRT requirements for India is given in next section.

To find out the effectiveness of decoupled control, during low voltage period, simuations are carried out and results are presented in this chapter.

7.2 LVRT Requirements in india

LVRT requirement is essential to be met by WTG when the grid voltage is temporarily reduced due to fault or large switching of load. The utilities (grid operators) impose grid code requirement on wind power operator to reduce the risk of voltage collapse and thereby reducing the chances of instability. The grid code for WTG has been derived from the original grid code developed for conventional power plants considering only synchronous generator. As per the Indian Grid Code, all the wind farms connected to 66 kV and above voltage level shall have the operating region as specified.

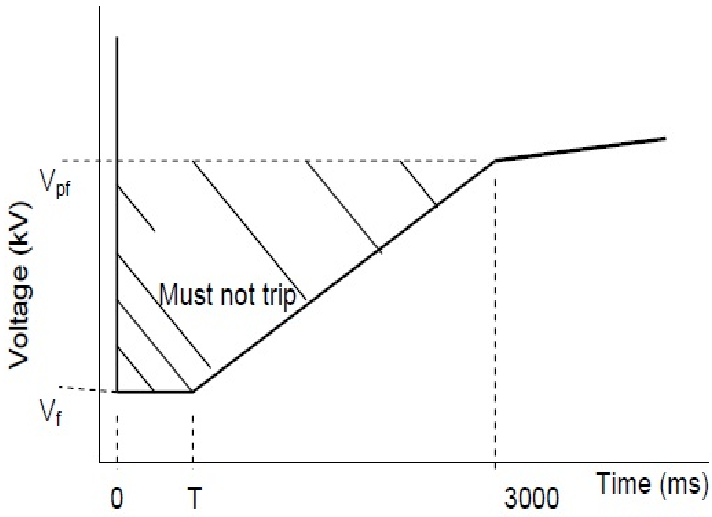

Figure 7.1: Grid Code Requirement

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V_f = 15% of Nominal System Voltage

V_{pf}=Minimum Voltages (80% of Nominal System Voltage)

Table 7.1: Fault Ride Through Characteristics

Nominal System Voltage (kV)	Fault Clearing Time (mS)	V_{pf} (kV)	V_f (kV)
400	100	360	60
220	160	200	33
132	160	120	19.8
110	160	96.25	16.5
66	300	60	9.9

The fault clearing time for various voltage levels are given in table (7.1). The reason behind laying down this requirement is that, the wind turbines must stay connected when a suddenly voltage fall occurs in the grid. If the wind turbine has been disconnected on the occurrence voltage dip, there will be loss of large amount of wind power, which may further drop in the voltage, which may lead loss of grid stability.

When a grid voltage dip appears and voltage recovers, LVRT requirement demands the following response from WTG plant.

- To remain connected to the grid, when line voltage is above the limit curve in Fig 7.1.
- To support the system voltage during fault condition by injecting reactive power.

7.3 Wind Power Model

Wind Power follows the Weibull distribution and the probability distribution can be estimated by Weibull function with 2 or 3 parameters. The captured aerodynamic power is given by equation 7.1. It depends on air density, swept area of wind turbine, the power coefficient and wind speed.

$$P_w = \frac{\rho}{2} A_r U_w^3 C_p(\lambda, \beta) \tag{7.1}$$

The wind power is a non-linear function, depends on few parameters. The wind turbine can be run either in constant speed mode or in constant power mode. The motivation behind the constant power assumption is that, power remains constant for any change in shaft speed. This has been achieved by varying the blade pitch. The effect on the output of the WTG models can be examined for the both constant power and constant torque.

7.4 Wind Turbine Model

There are various literatures available on the modelling of the Induction Generator (IG). Starting from 3^{rd} order to 7^{th} order model of DFIG is available. According to the requirement of accuracy, different order of DFIG is used in the study. Here 5^{th} order $d-q$ DFIG model is used for the study purpose, as it has very good accuracy in simulating the rotor speed, electromagnetic torque, both active & reactive power and stator current. Control of electromagnetic torque allows the speed control.

Independent control of the electromagnetic torque through the control of a single variable. It is possible through the rotor current i_{dr} by the selection of an appropriate reference frame in the controller of the back-to-back converter. The equation for the electromagnetic torque T_{em} is given in terms of the rotor current.

$$T_{em} = \frac{3PL_m}{4L_s}(\psi_{qs}i_{dr} - \psi_{ds}i_{qr}) \tag{7.2}$$

Using appropriate reference frame, the torque equation can be decoupled.

$$T_{em} = \frac{3PL_m}{4L_s}(\psi_{qs}i_{dr}) \tag{7.3}$$

The control of i_{dr} may also be simplified considerably through the careful design of the d-axis and q-axis voltages, such that

$$v_{dr} = v'_{dr} - (\omega - \omega_r)\frac{L_m}{L_s}(\psi_{qs}) + (\omega - \omega_r)\frac{L_\alpha}{L_s}(i_{qr}) \tag{7.4}$$

$$v_{qr} = v'_{qr} - \frac{L_m}{L_s}(p\psi_{qs}) - (\omega - \omega_r)\frac{L_\alpha}{L_s}(i_{dr}) \tag{7.5}$$

Where v'_{dr} and v'_{qr} are auxiliary signals in the controller reference frame and are the outputs from the d-axis and q-axis proportional integral current controllers respectively.

$$v'_{qr} = (i^*_{qr} - i_{qr})(K_{P2} + \frac{K_{I2}}{p}) \tag{7.6}$$

$$v'_{dr} = (i^*_{dr} - i_{dr})(K_{P1} + \frac{K_{I1}}{p}) \tag{7.7}$$

7.5 Wind Turbine Inertial Response

The inertial response control loop is added to the DFIG active power control loop, as shown in 7.2. The intent is that, when system frequency changes, not only do the synchronous generator respond to this change, the wind plant also quickly changes its output active power to contribute in the frequency restoration process during short term frequency fluctuation. The output active power reference is predefined for different wind speeds. With the given DFIG rotor speed, optimal power signal $P_{optimal}$ is obtained and compared with measured output electrical power. The error signal is regulated by the rotor side converter controller to obtain the required rotor current I_{qr}. The inertial control loop is responsible for sending additional power regulation signal ΔP_{ref} to the rotor side converter controller. When the load on system increases, leading to a frequency drop. The inertial control loop sends additional active power ΔP_{ref} to the DFIG active power reference P_{ref}.

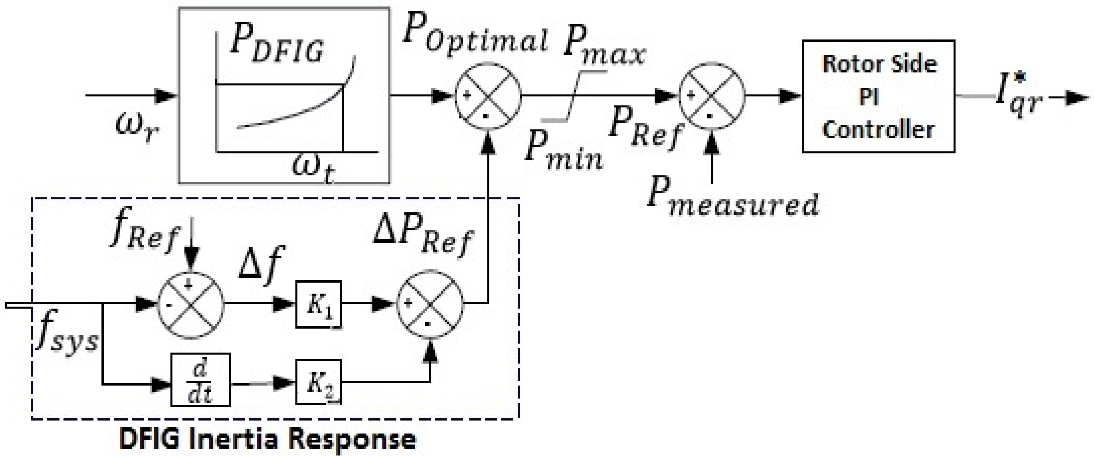

Figure 7.2: Primary Frequency Control

The reactive power is directly related with the voltage control. The rotor side controller supports the grid voltage and also fulfils the power factor control requirement.

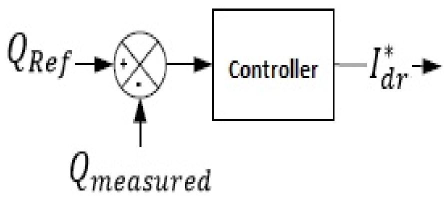

Figure 7.3: Voltage Control

The rotor controller for d-axis and q-axis are given in figure 7.4.

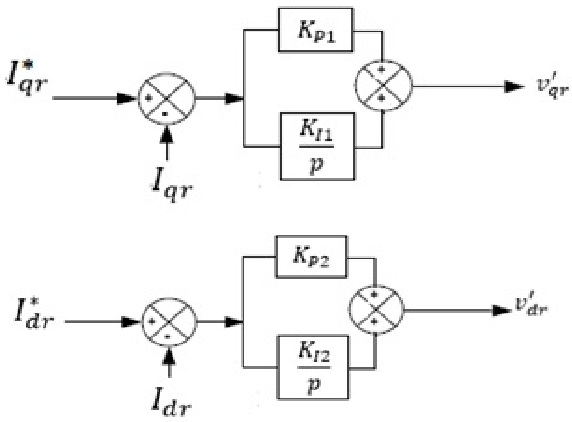

Figure 7.4: PI Controller for d and q axis

7.6 Pitch Angle Control

Pitch angle control of the wind turbine mimics the governor control of synchronous machine. Pitch angle control is sluggish in response and contributes in the steady state frequency error control. The DFIG, in this case, operate on the sub-optimal active power operation to reserve some power for dynamic frequency control. If WTG runs on the MPPT point, it will run on one speed only. But if, it is operated at sub-optimal point, there will be two speeds for a given power output, it can be seen and verified from the graph in figure 7.5. So, there is a trade-off between the maximum extracted energy and the dynamic response capability of the WTG. It has advantage that, if WTG is operated at sub-optimal point at the higher speed, there will be additional power available. This additional power comes from two stream, one from the stored kinetic energy of the rotor of WTG and second is the difference between Optimal and suboptimal power point, i.e. (P_{MPPT}-$P_{suboptimal}$). The Pitch angle control loop diagram is given below in figure 7.6

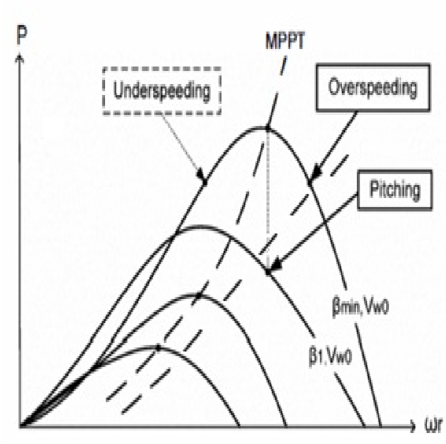

Figure 7.5: MPPT Power Control of Wind Turbine

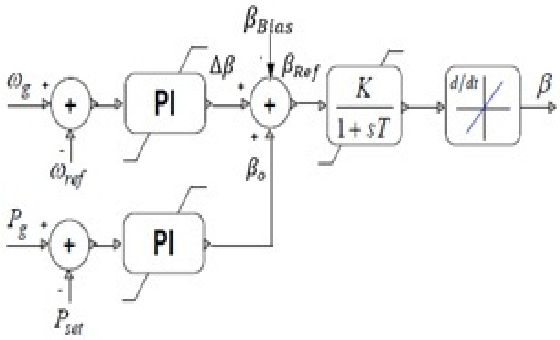

Figure 7.6: Pitch Control Loop

Pitch angle is regulated to follow the β_{ref}. It is given by equation (7.8)

$$\beta_{ref} = \beta_0 + \Delta\beta + \beta_{Bias} \tag{7.8}$$

Where, $\Delta\beta$ comes from the β - Frequency curve. β_{Bias} is additional angle to keep the WTG away from the optimal point, at sub-optimal point. This may be positive or negative, depends on whether the wind power is deficient or surplus with respect to the predicted power. DFIG droop characteristics is similar to that of the synchronous generator. The frequency falls as the load on generator increases. To reduce the steady state frequency error, the power reference P_{Ref} is changed by changing the P_{LRef}.

The $\beta - P_{Ref}$ reference curve is calculated and stored in the form of equation. For a given β value, the curve gives the reference power P_{Ref}. The β value is decided based on how much WTG should be deloaded to keep away from the MPPT point. The initial pitch angle (β_0) decides how much power is reduced. As the load increases, pitch angle gets adjusted to reach the MPPT point.

7.7 Decoupled Control Structure

In DFIG, the stator is directly connected to the grid and the slip ring rotor is connected to the grid through back to back AC-DC-AC converter as shown in figure . The converter consists of two converter, Rotor Side Converter (RSC) and Grid Side Converter (GSC), connected by a DC Link. A harmonic filter and line inductor is connected between the Grid and Grid Side Converter to reduce the harmonics and fault current. A craw bar is used to limit and control the overcurrent and over voltages in the rotor circuit. A DC chopper is used in the DC Link to limit the DC link overvoltage

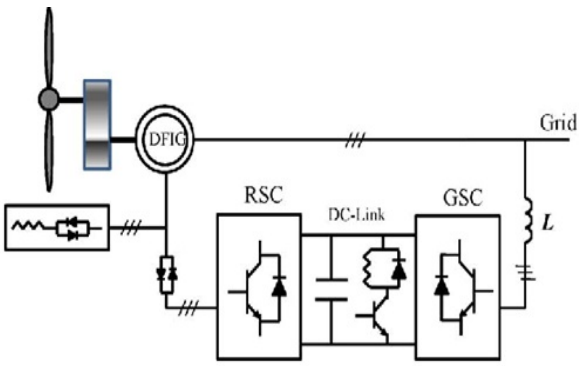

Figure 7.7: DFIG Scheme

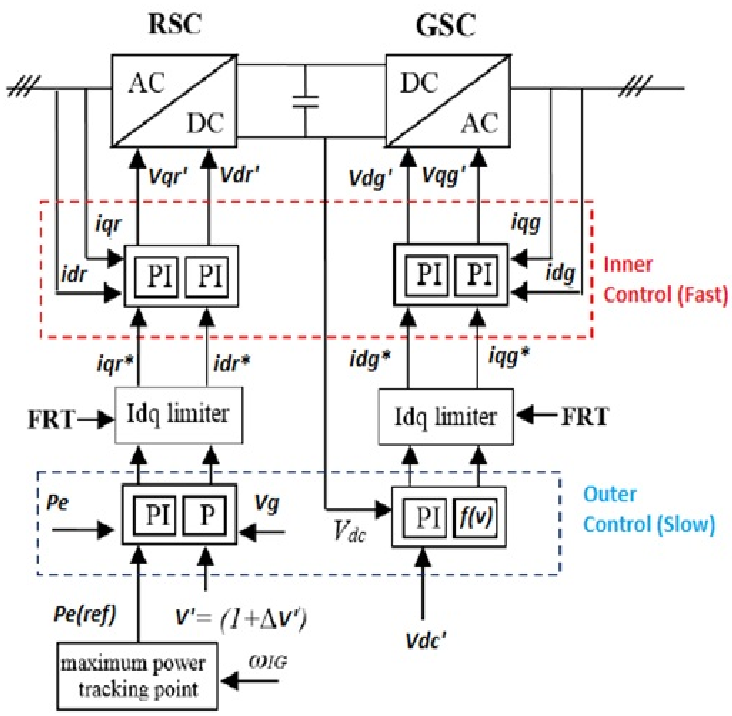

Figure 7.8: Decoupled Control Structure

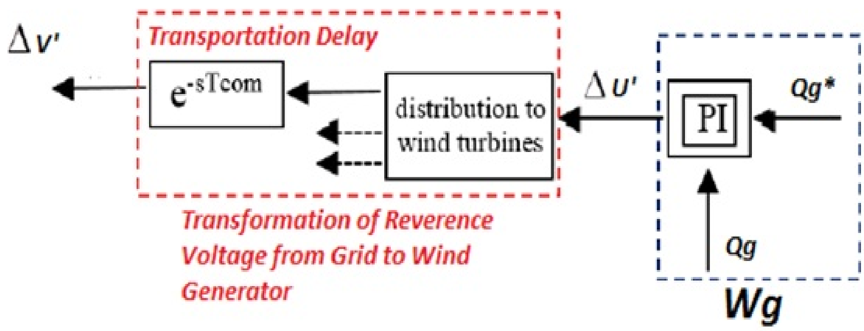

Figure 7.9: Grid Voltage Deviation Control

7.8 Control Scheme

The DFIG Control scheme is illustrated in figure (7.8) and (7.9). The i_{dr} and i_{qr} are the d and q axis currents of the RSC. Similarly,i_{dg} and i_{qg} are the d axis and q axis currents of the GSC. V_{dc} is the DC link voltage of the converter. P_e is the electrical active power. V_{wt}^{+} is the positive sequence voltage of the grid at the MV terminal. The rotor current controls the active power and the grid terminal voltage, whereas the grid side current i_{dg} controls the DC voltage V_{dc} and i_{qg} used to support the reactive power on the event of fault.

Both RSC and GSC are controlled by two separate controller with two independent loops as shown in figure (7.8). The outer control, which is slow, calculates the $d-q$ frame current reference and faster inner controller generates the reference ac voltage for two converters. The active power $P_{e(ref)}$ is calculated from the MPPT Control scheme. The change in positive sequence voltage of grid is calculated using reactive power requirement as shown in figure (7.9).

RSC and GSC, both are controlled by 2-level controller. The outer controller is slow and calculates the reference current in $d-q$ reference frame ($i^{'}_{dr}$, $i^{'}_{qr}$, $i^{'}_{dg}$, and $i^{'}_{qg}$), whereas the fast inner control loop generates the reference voltage for converter. Based on the speed of Wind Turbine Generator (WTG), the maximum possible power that can be extracted is found out. This power is then compared with the actual power and difference (error) is generated. This error is then fed to the PI controller, which generates the current reference $i^{'}_{dr}$. In the other part, the voltage reference ($V^{'} = (1 + \Delta V^{'})$ is compared with the positive sequence voltage at the MV terminal of the grid (V^{+}_{wt}). The difference is the error. The error is then fed to the PI controller and it generates the the current reference $i^{'}_{qr}$. The voltage deviation is calculated from the reactive power requirement as shown in figure (7.9).

The function of GSC is to maintain the DC link voltage V_{dc} of DFIG converter. The actual DC link voltage V_{dc} is compared with reference and difference is calculated, which is an error. The error is then processed in PI controller to generate the current reference signal $i^{'}_{dg}$.

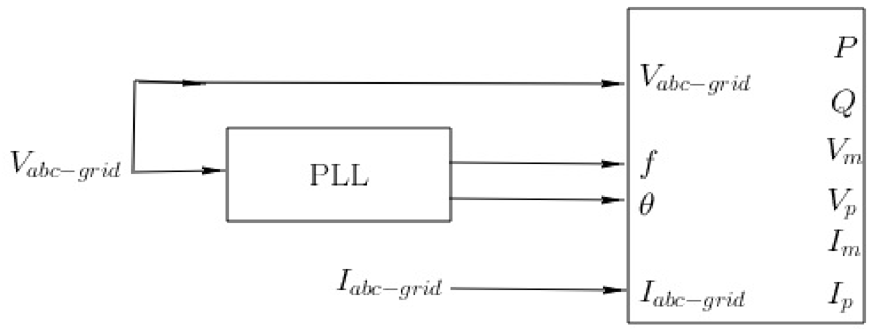

Figure 7.10: Measurement Block

Figure (7.10) shows the measurement block. It measures the three phase voltages and currents. The frequency f and angle θ is derived from 3-Phase voltages using PLL. It also computes active power P, reactive power Q, magnitude of voltage V_m, phase of voltage V_p, magnitude of current I_m and phase of current I_p.

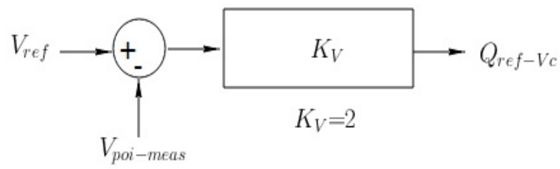

Figure 7.11: Reactive Power Reference for Voltage Control

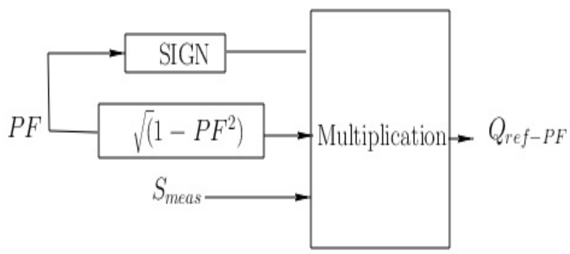

Figure 7.12: Reactive Power Reference for PF Control

The purpose of reactive power control is to achieve voltage regulation, power factor (PF) regulation and meet reactive power demand of grid under varying load condition. The outer control loop generates the reference signal based on the reactive power demand. The reactive power demand can be selected based on the desired value of voltage, PF or reactive power demand of grid. Figure (7.11) and (7.12) shows the outer control loop for generation reactive power reference. This reference is then fed to the next level control loop to generate the voltage deviation signal dU_{ref} as shown in figure (7.13).

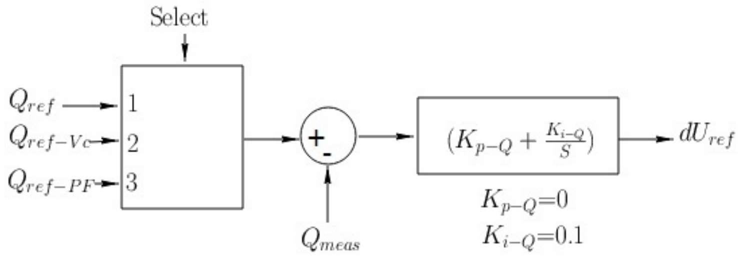

Figure 7.13: Selection of Reactive Power Referencel

In decoupled control structure, the responsibility of various control objectives is divided and assigned to RSC and GSC. The voltage control and active power control is assigned to RSC. The voltage deviation, difference between the positive sequence grid voltage and reference voltage, is used to generate the d - axis current reference signal i'_{dr}. In the same way, the Maximum Power Point is tracked by comparing P_{eRef} with actual P_e. The difference is then fed to the slow response outer PI controller to generate the q - axis rotor current reference i'_{qr}. It is shown in the figure (7.14) and (7.15) respectively.

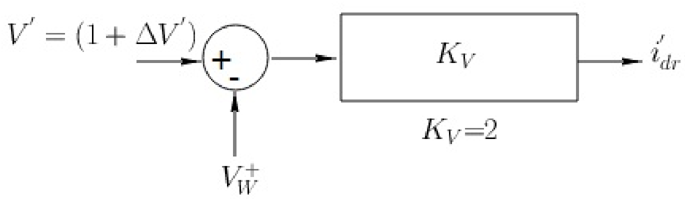

Figure 7.14: Selection of Reactive Power Referencel

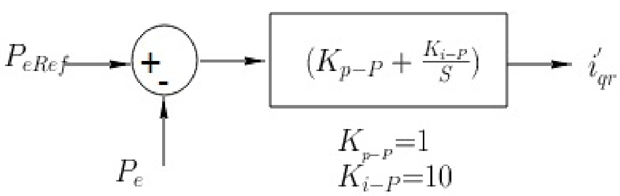

Figure 7.15: Selection of Reactive Power Referencel

In the next level, which is fast inner control loop, the i'_{dr} and i'_{qr} is compared with acutal currents i_{dr} and i_{qr} and reference voltages v_{dRef} and v_{qRef} is generated. This voltages are then converted in to 3- Phase Voltage signals. It is shown in the figure (7.16) and (7.17).

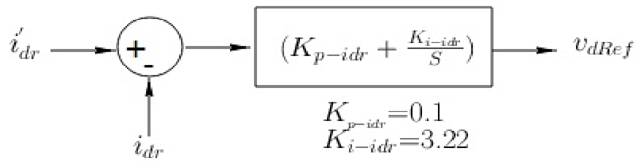

Figure 7.16: PI controller for v_{dRef}

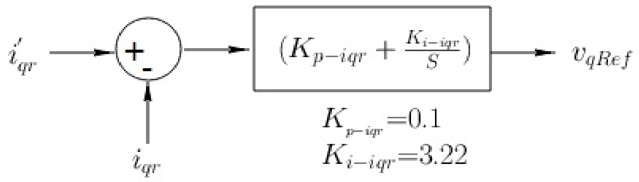

Figure 7.17: PI controller for v_{qRef}

In a similar way the control signal for GSC is generated for DC link Voltage V_{dc} control. It is explained with the help of figure (7.18), (7.19) and (7.20). The reference signal i'_{dg} is generated using DC link voltage error signal. It is then compared with the actual current i_{dg} and the reference signal dV_{dRef} is generated. It actually compensates the active power deficit to maintain the DC link voltage. In the same way the reference signal i'_{qg} is generated. It is then compared with the actual current i_{qg} to generate reference signal dV_{qRef}. In normal operating condition, the q axis reference is made to zero to provide zero reactive power to the grid, but under fault condition, the Fault Ride Through (FRT) signal is activated and it makes the q axis reference signal non-zero, keeping in view the capacity limitation of GSC converter.

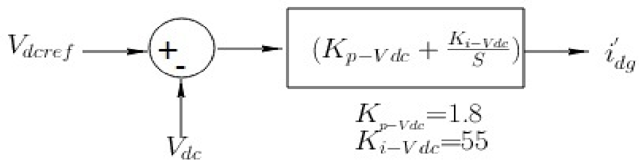

Figure 7.18: PI controller for DC Link Voltage Regulation

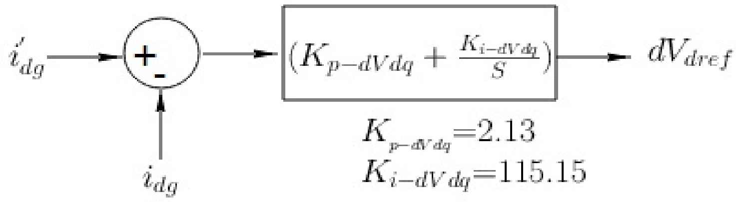

Figure 7.19: PI controller for dV_{dRef}

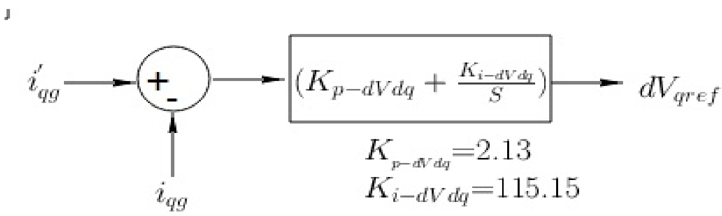

Figure 7.20: PI controlerl for dV_{qRef}

Under the unbalance condition, there will be negative and zero sequence of voltages and currents. It is used to compensate the voltage unbalance. It's functioning is described using figure (7.21), and (7.20) (7.23).

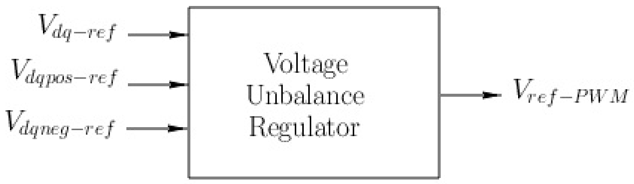

Figure 7.21: PWM reference for Unbalance Voltage Condition

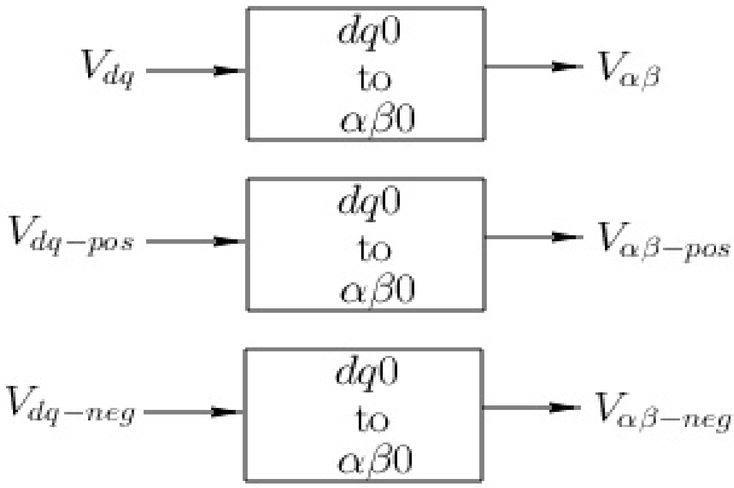

Figure 7.22: $dq0$ to $\alpha\beta$ Conversion

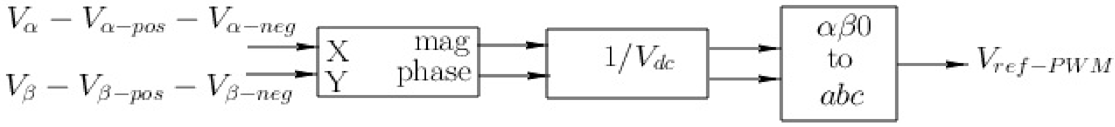

Figure 7.23: $\alpha\beta$ to ABC Conversion

7.9 Test System

A 4-Bus EPRI test system is selected for the simulation purpose. The Wind Farm, with 45 DFIG Wind Generators, each of 1.5 MW capacity, is connected at Bus-1. Whereas the Conventional Generator and load is placed at Bus-2. The load (30 MW, 15 MVAR) is connected to Bus-3 and Bus-4. An unbalance fault L-L-G is created at Bus - 3 and the effectiveness of control action is evaluated using simulation results. EMTP - RV version 3.6 is used for simulation. The voltages under unbalance fault condition at bus-1 and at Wind Turbine terminal are captured along with various control signals and is presented here.

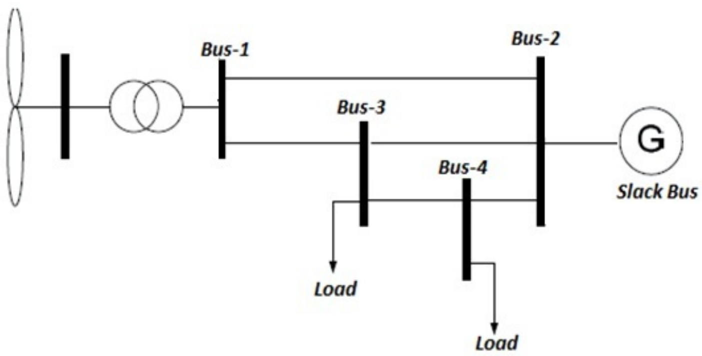

Figure 7.24: 4-Bus EPRI Test System

7.9.1 Test Parameters

Wind Turbine Capacity = 1.5 MW, Nominal Voltage of WTG = 575 V, Stator Resistance = 0.023 p.u., Stator Inductance = 0.18 p.u., Magnetizing Inductance = 2.9 p.u., Generator Inertia H = 0.685 s, Friction Factor F = 0.01 p.u., Pair of Poles = 3, Line Filter Capacity = 120 kVAr, Grid Side Converter Nominal Current = 0.8 p.u., Nominal DC Bus Voltage V_{DC}= 1150 Volts, Wind Turbine Inertia Constant = 4.32 s, Shaft Spring Constant = 1.11 Torque/rad, Shaft Mutual Coupling =1.5 Mech Torque/rad, Turbine Initial Speed = 1.2 p.u., $k_{p(DC)}$ = 8, $k_{i(DC)}$ =400, $k_{p(RSC)}$=0.6, $k_{i(RSC)}$=8,$k_{p(GSC)}$ = 0.83, $k_{i(GSC)}$ =5, $k_{(Pitch)}$ = 160, $k_{p(beta)}$ = 3, $k_{i(beta)}$ = 30

7.10 Simulation Results and Discussion

To understand the response of WTG under fault condition, a fault is created at Bus-3 of the test network and different parameters are observed. Two cases, each with different fault duration, are presented here to demonstrate the compliance of grid code by Wind Turbine Generator.

7.10.1 Case-A: L-L-G Fault of 250 ms Duration

In Case-A, the fault time is kept at 250 ms. According to grid code, the WTG shall survive fault for less than 1 *second*. It has been observed from the various graph that, WTG is effectively ride through the fault. Unbalance fault on gives rise to the negative and zero sequence voltage and current. It can be observed in figure (7.25) and (7.26).

The functioning of Grid Side Converter (GSC) is given in figure (7.27) and (7.28). The active and reactive power through rotor circuit is given in figure (7.29). The frequency is deviated from synchronous frequency during the fault and is given in figure (7.30). During the fault, the active power and reactive power supply to the grid is affected, which in turn affect the DC link voltage. The DC link voltage increases, as the active power supply during fault reduces. The rise in V_{dc} can be seen in figure (7.31). The pitch angle during the fault is not changed as the fault time is small and this can be seen in figure (7.32). The moment fault occurs, the fault is sensed by wind turbine controller and this activates the Fault Ride Through signal as shown in figure (7.33). The Wind Generator and Wind Turbine speed during fault increases due to decrease in active power supply to the grid with constant wind speed, i.e. constant mechanical power. This gives rise to rotor acceleration as shown in figure (7.34). The active power fed to grid by WTG, reactive power fed to grid by WTG and grid voltage during the fault is given in figure (7.35). Finally, the reduced wind turbine voltage during the fault is given in figure (7.36).

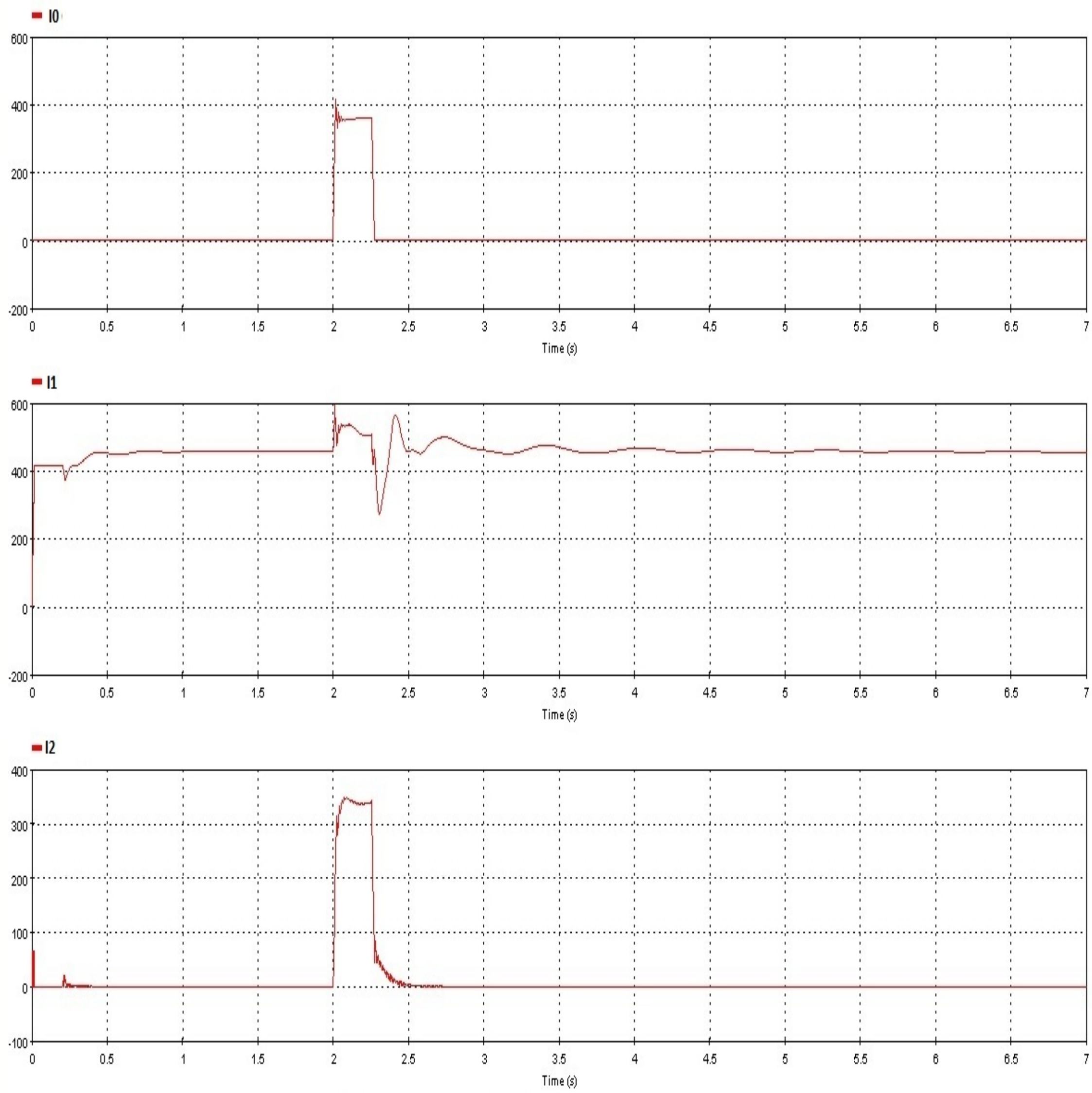

Figure 7.25: Positve, Negative and Zero Sequence Current Under Unbalance Condition

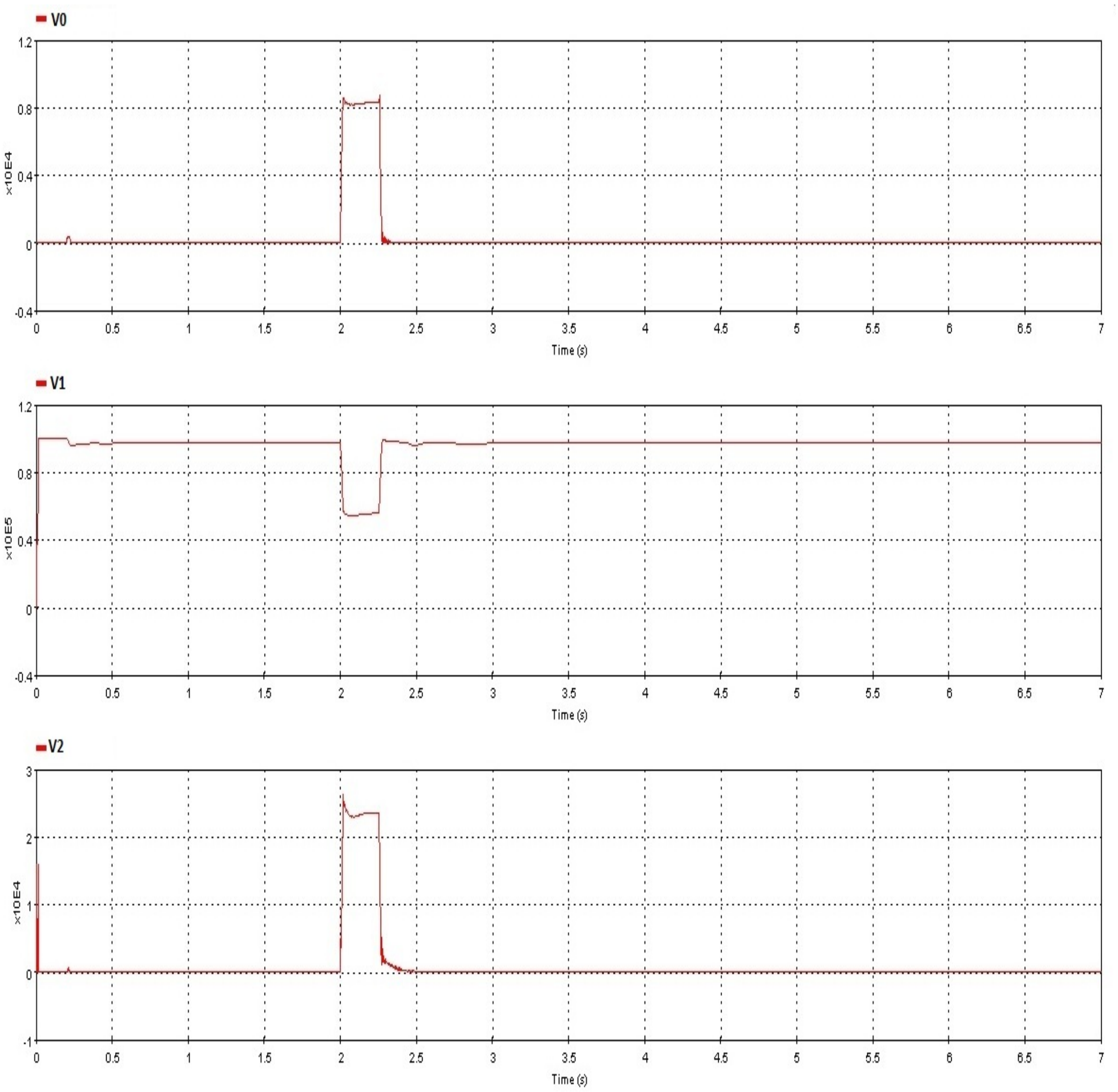

Figure 7.26: Positve, Negative and Zero Sequence Voltage Under Unbalance Condition

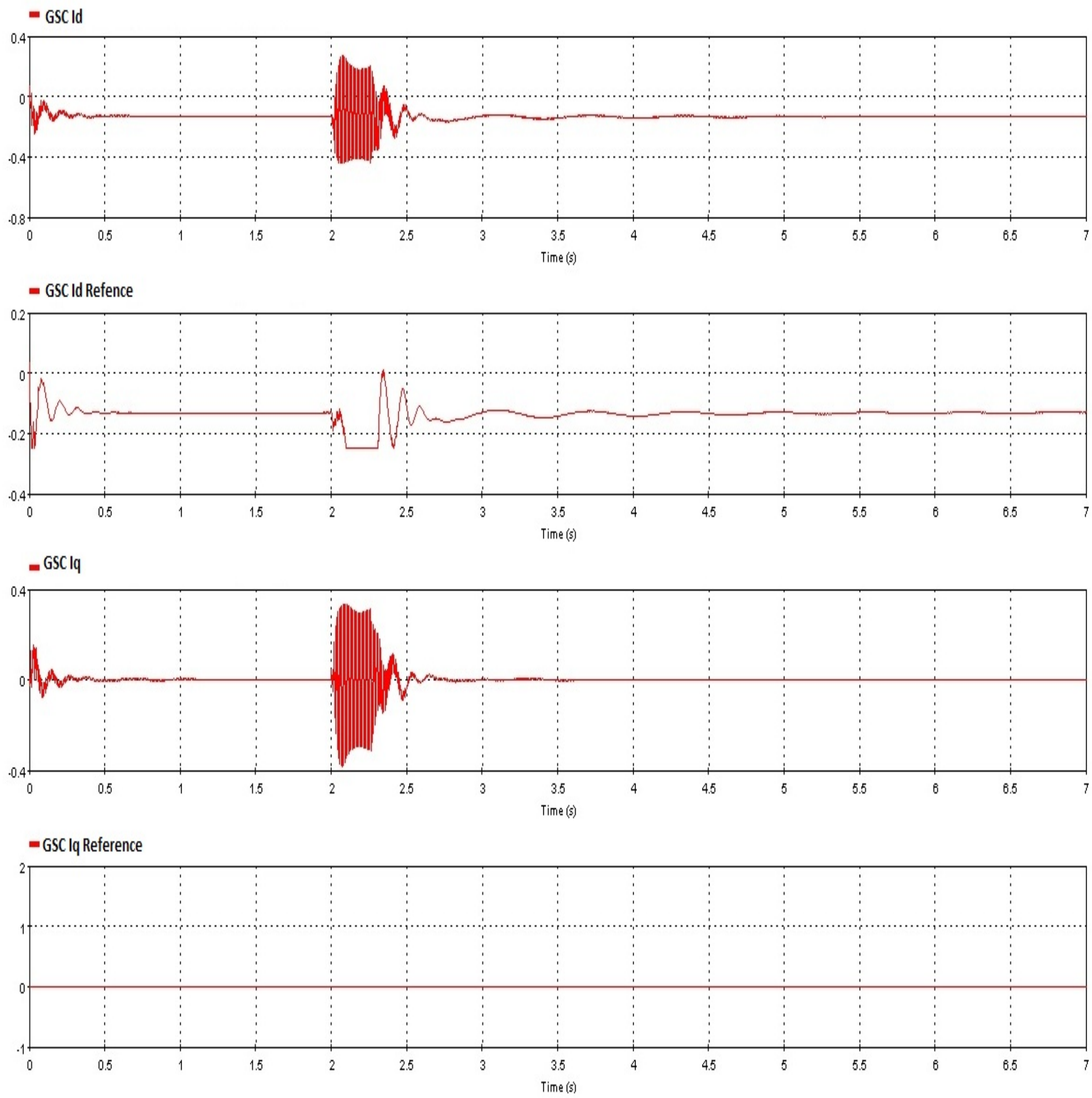

Figure 7.27: Grid Side Converter - Outer Loop Currents

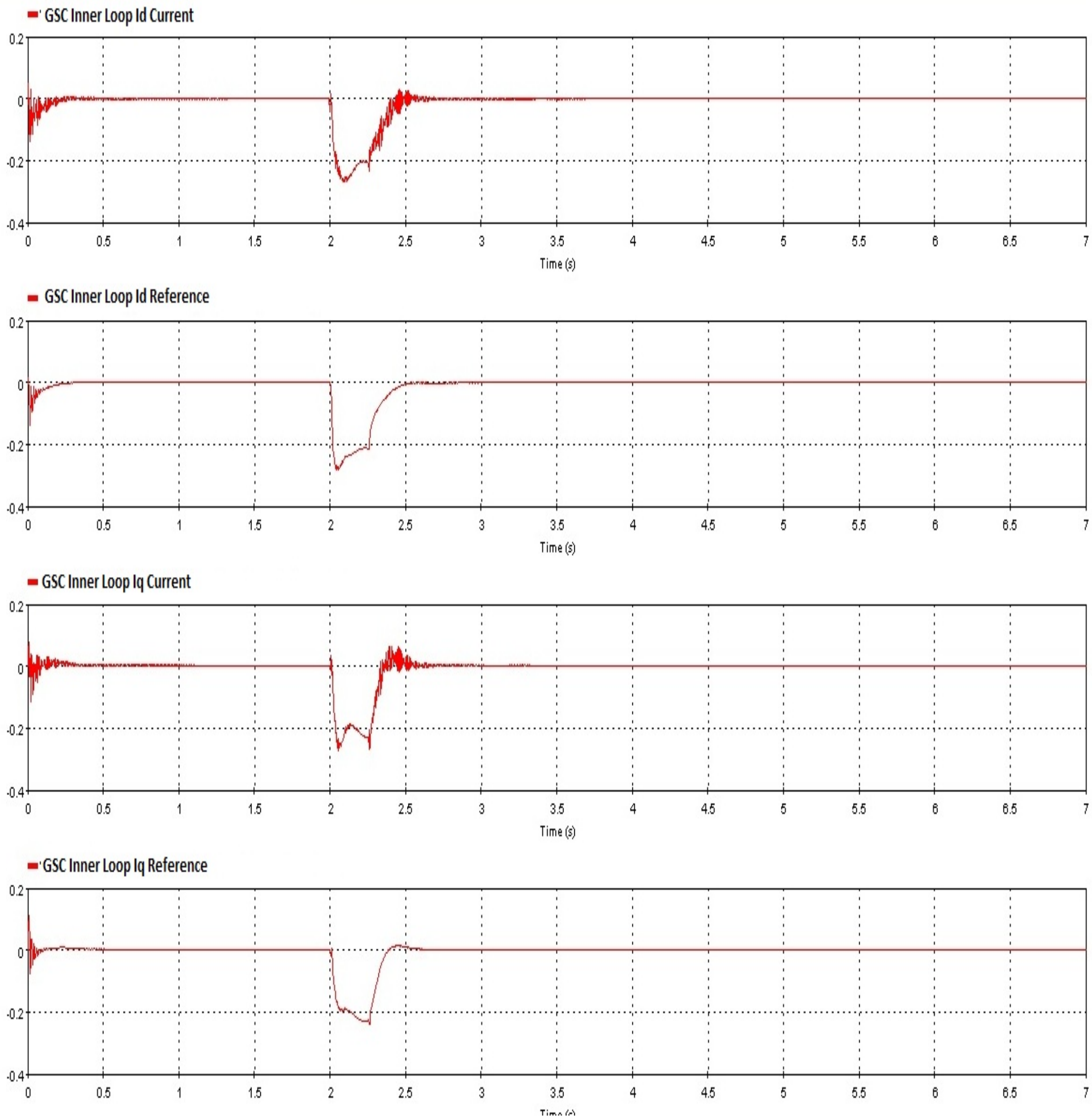

Figure 7.28: Grid Side Converter - Inner Loop Currents

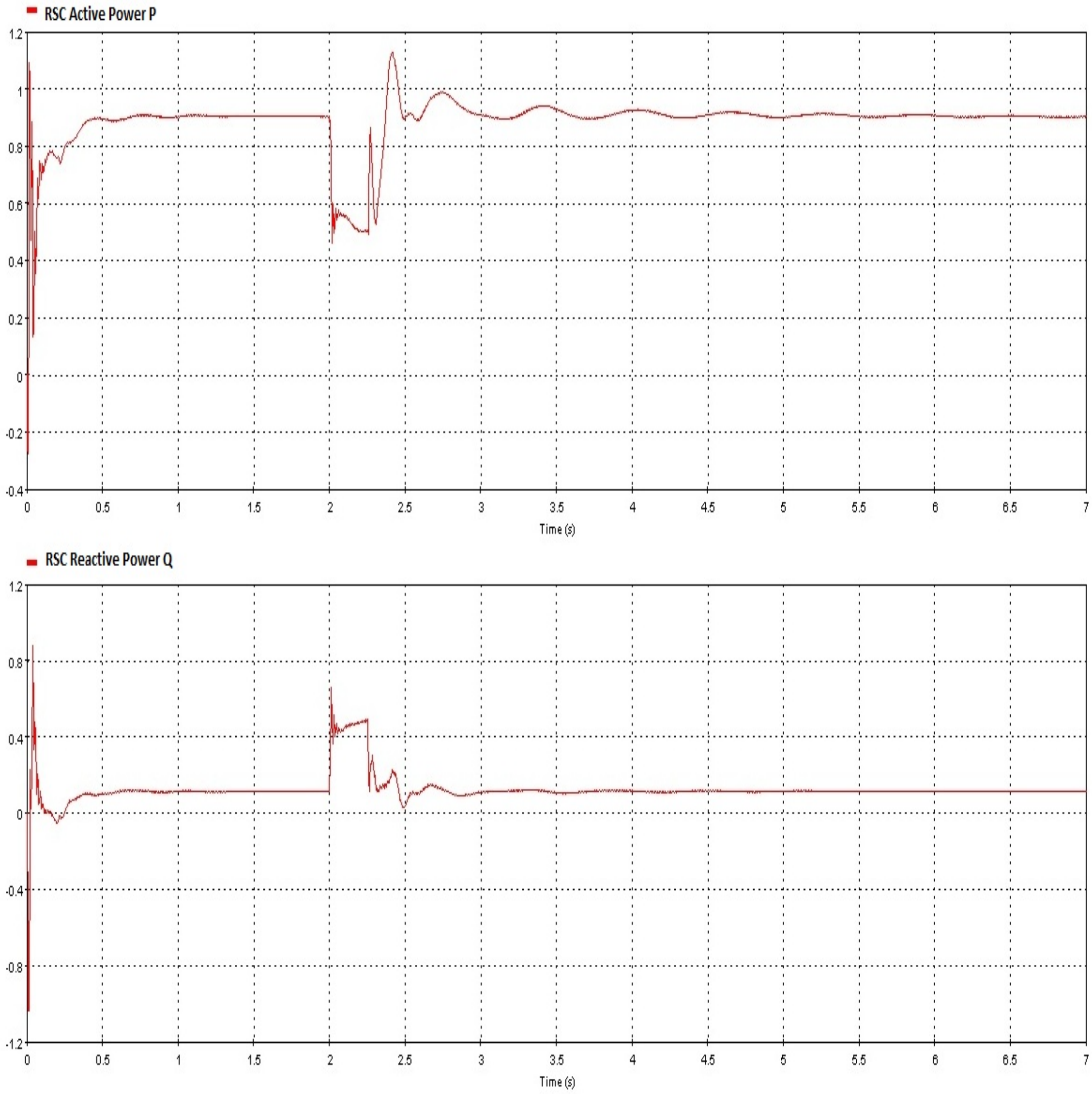

Figure 7.29: Active and Reactive Power of RSC during Fault

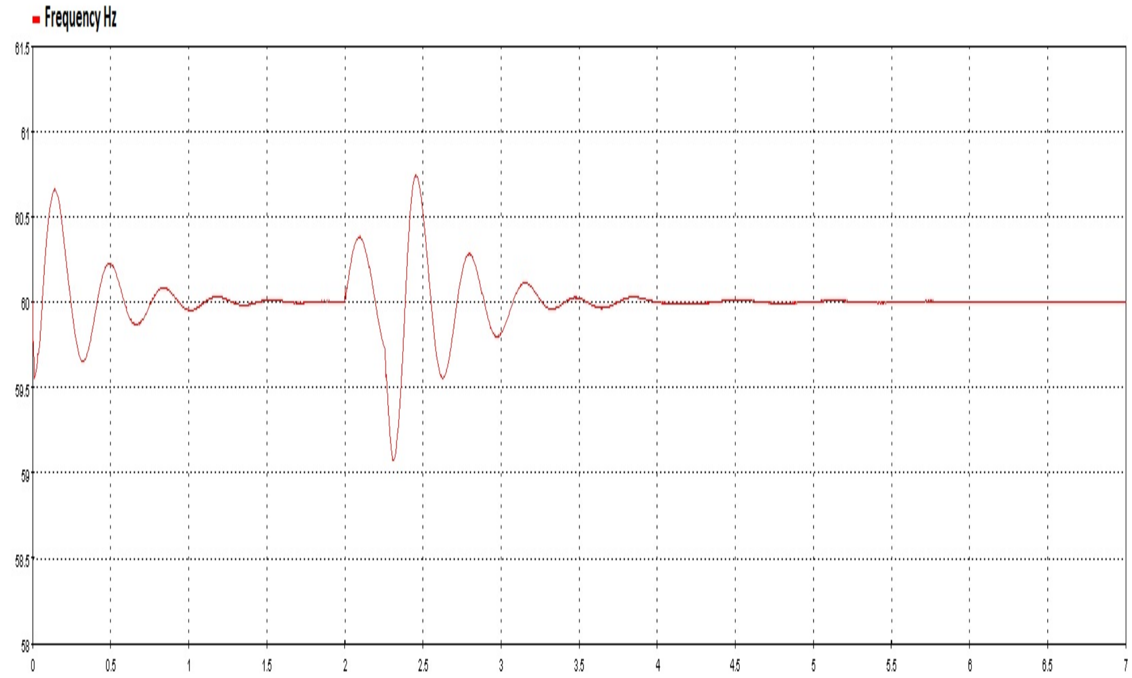

Figure 7.30: Frequency Deviation During Fault

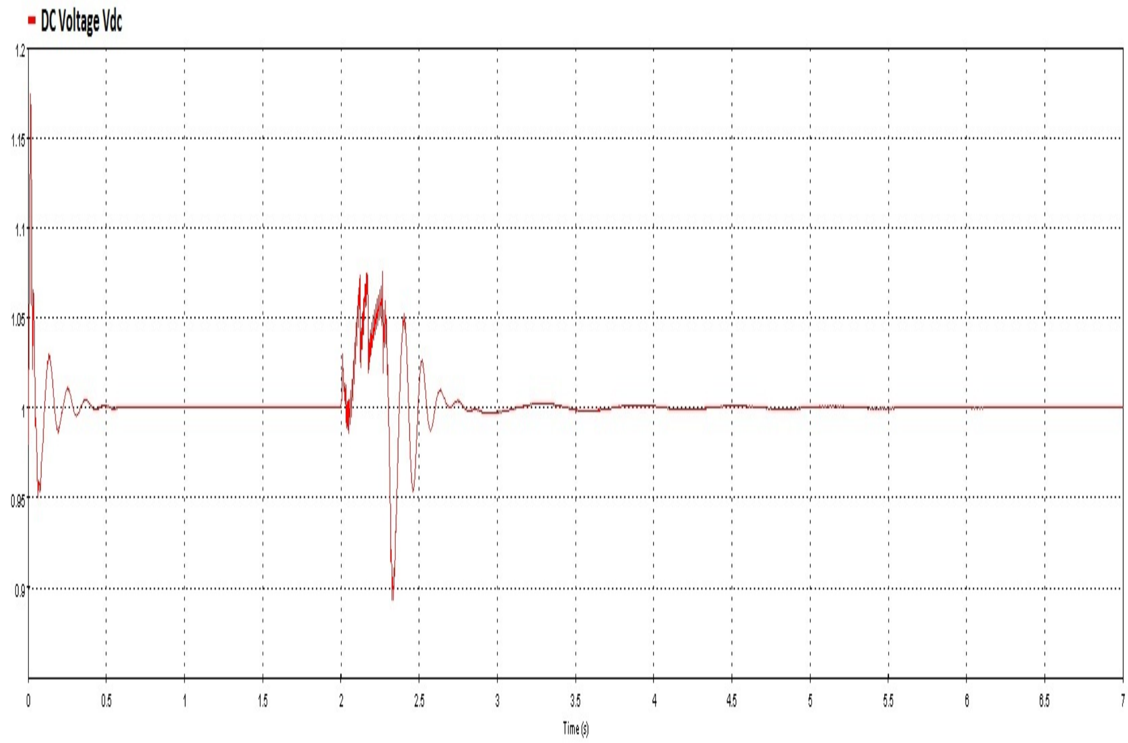

Figure 7.31: DC Link Voltage Deviation due to Fault

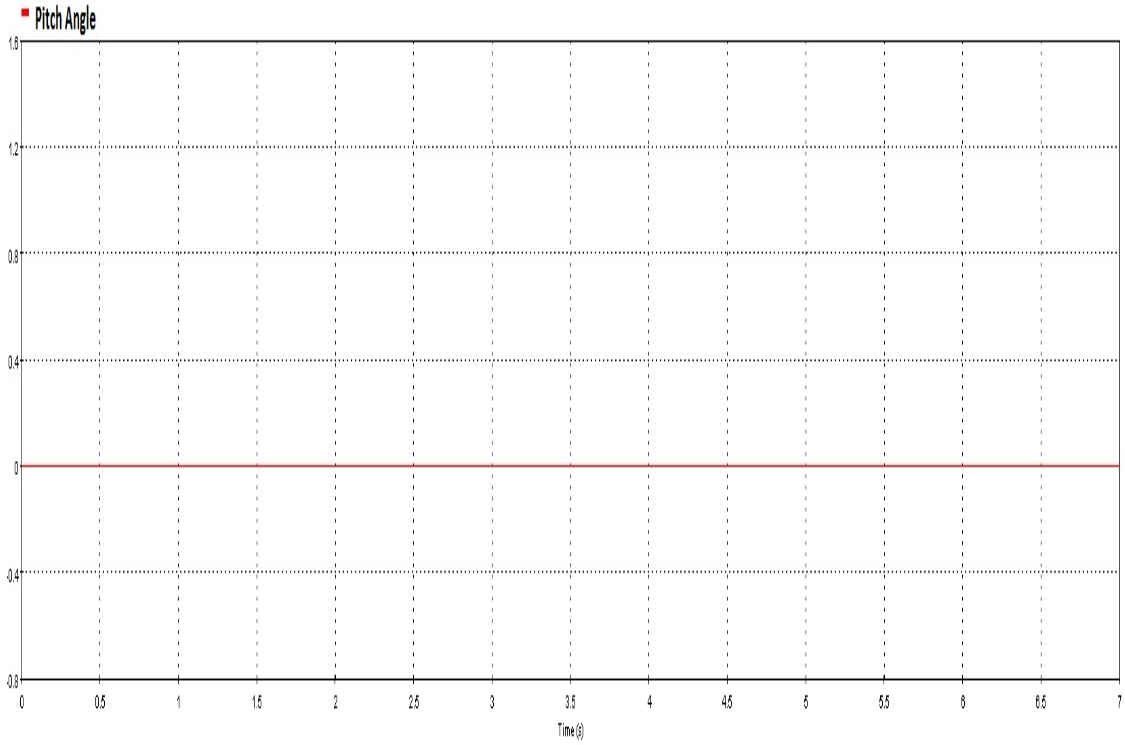

Figure 7.32: Pitch Angle Variation due to Fault

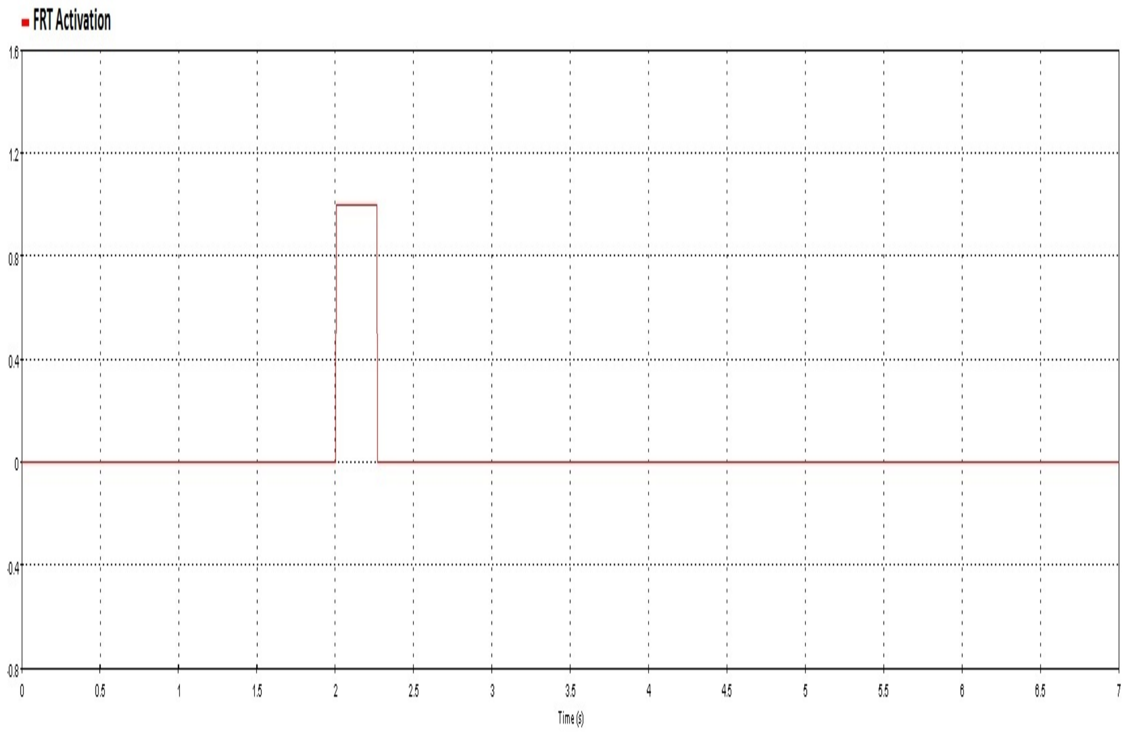

Figure 7.33: Fault Ride Through Activation

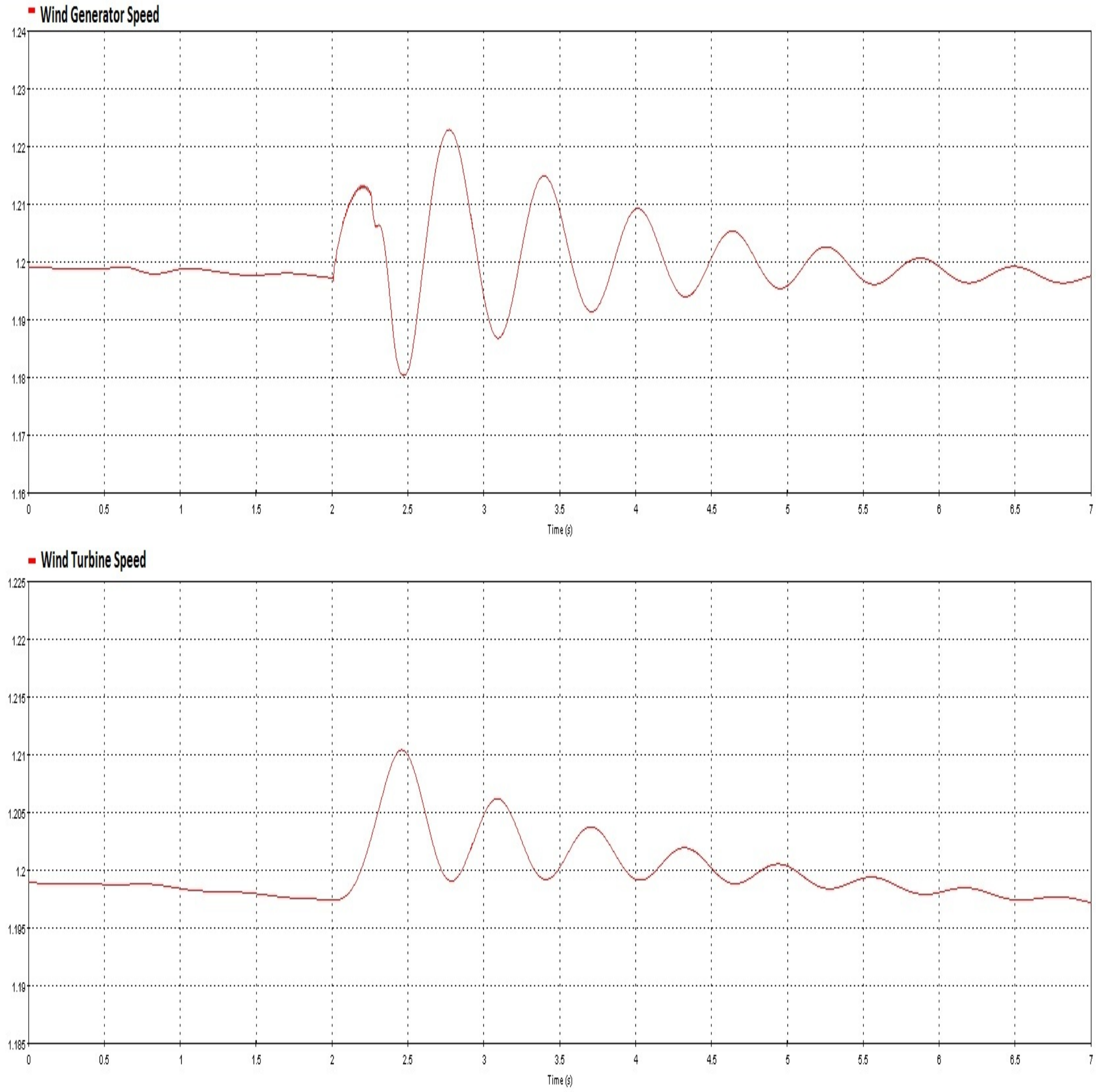

Figure 7.34: Wind Generator and Wind Turbine Speed Deviation during Fault

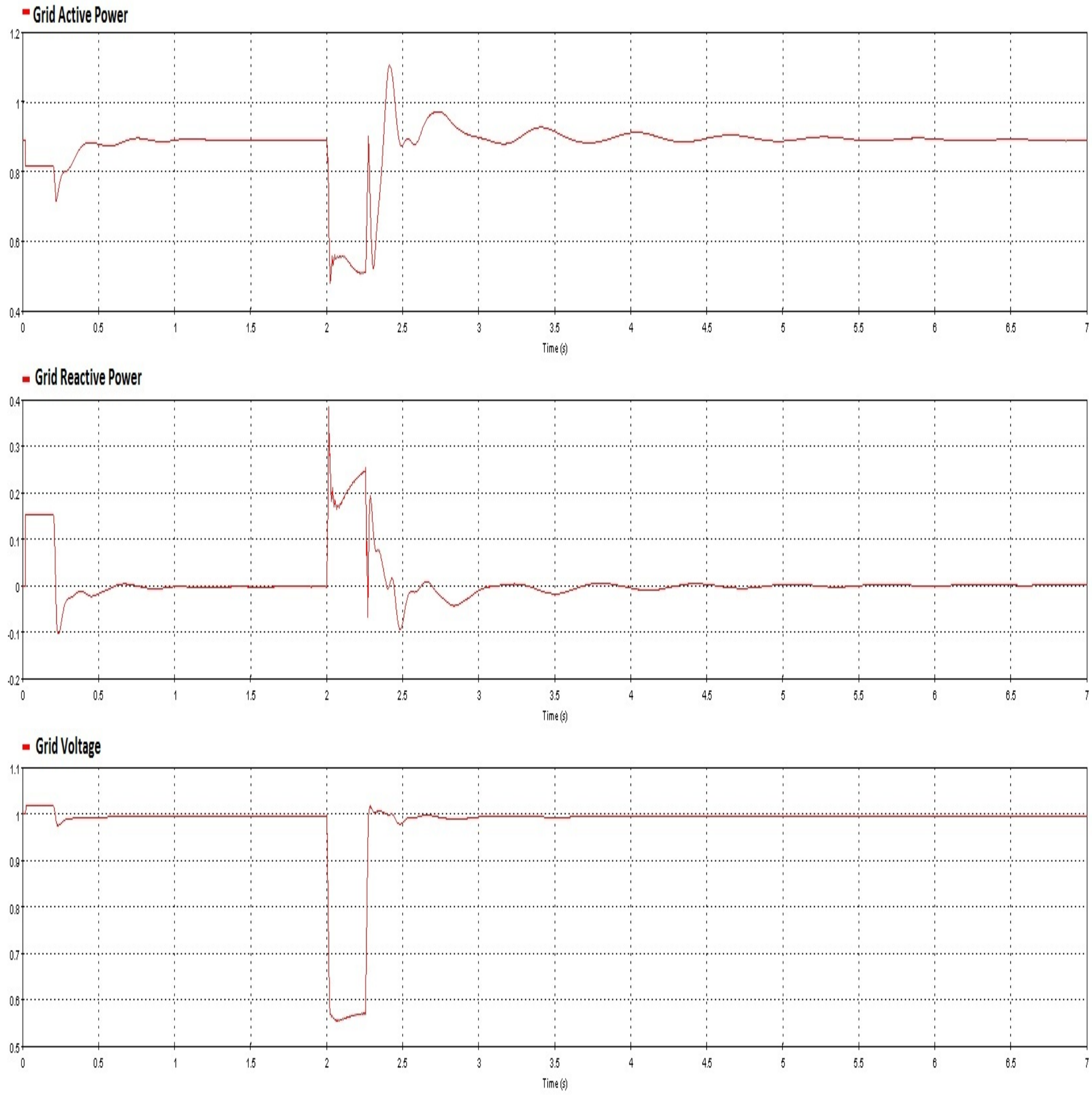

Figure 7.35: Grid Active Power, Reactive Power and Voltage during Fault

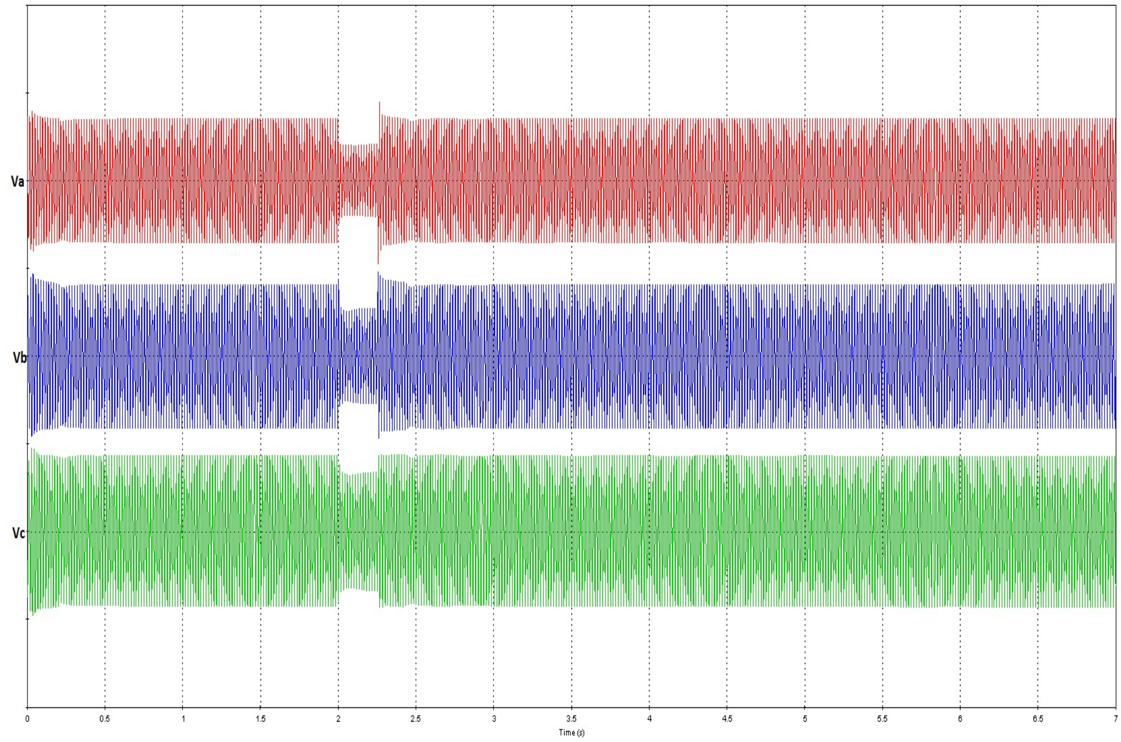

Figure 7.36: Wind Turbine Voltage during Fault

7.10.2 Case-B: L-L-G Fault of 1.5 *Seconds* Duration

In Case-B, the fault time has been set to 1.5 *seconds*. According to grid code, the WTG shall survive fault for less than 1 *second*. It has been observed from the various graph that, WTG cannot ride through the fault, as the fault time is higher than (1 *second*) the grid code requirement to survive the fault. Unbalance fault gives rise to the negative and zero sequence voltage and current. It can be observed in figure (7.37) and (7.38). The functioning of Grid Side Converter (GSC) is given in figure (7.39) and (7.40). The active and reactive power through rotor circuit is given in figure (7.41). It can be observed that the FRT signal remains activated for fault period. The frequency is deviated from power frequency during the fault and is given (7.42). During the fault, the active power and reactive power supply to the grid is affected, which in turn affect the DC link voltage, the DC link voltage increases and then it decreases and oscillates at high frequency. The controller cannot regulate the V_{dc} during the fault and higher variation is observed. The variation in V_{dc} can be seen in figure (7.43). The pitch angle during the fault is not changed for initial time, but after some time, it starts increasing as the speed of WTG cannot be maintained. As the fault time is high, the pitch angle rises and this can be seen in figure (7.44). The moment fault occurs, the fault is sensed by wind turbine controller and this activates the Fault Ride Through signal as shown in figure (7.45). The Wind Generator speed and Wind Turbine speed during fault increases due to decrease in active power supply to the grid with constant wind speed, i.e. constant mechanical power. This gives rise to rotor acceleration as shown in figure (7.46). The speed of WTG cannot be recovered after the fault in this case due to higher fault duration. The active power and reactive power fed to the grid by WTG and grid voltage during the fault is given in figure (7.47). In this case the active and reactive power fed to the grid finally reduced and couldn't come back to the rated power due to higher fault time. Finally, the reduced wind turbine voltage during the fault is given in figure (7.48).

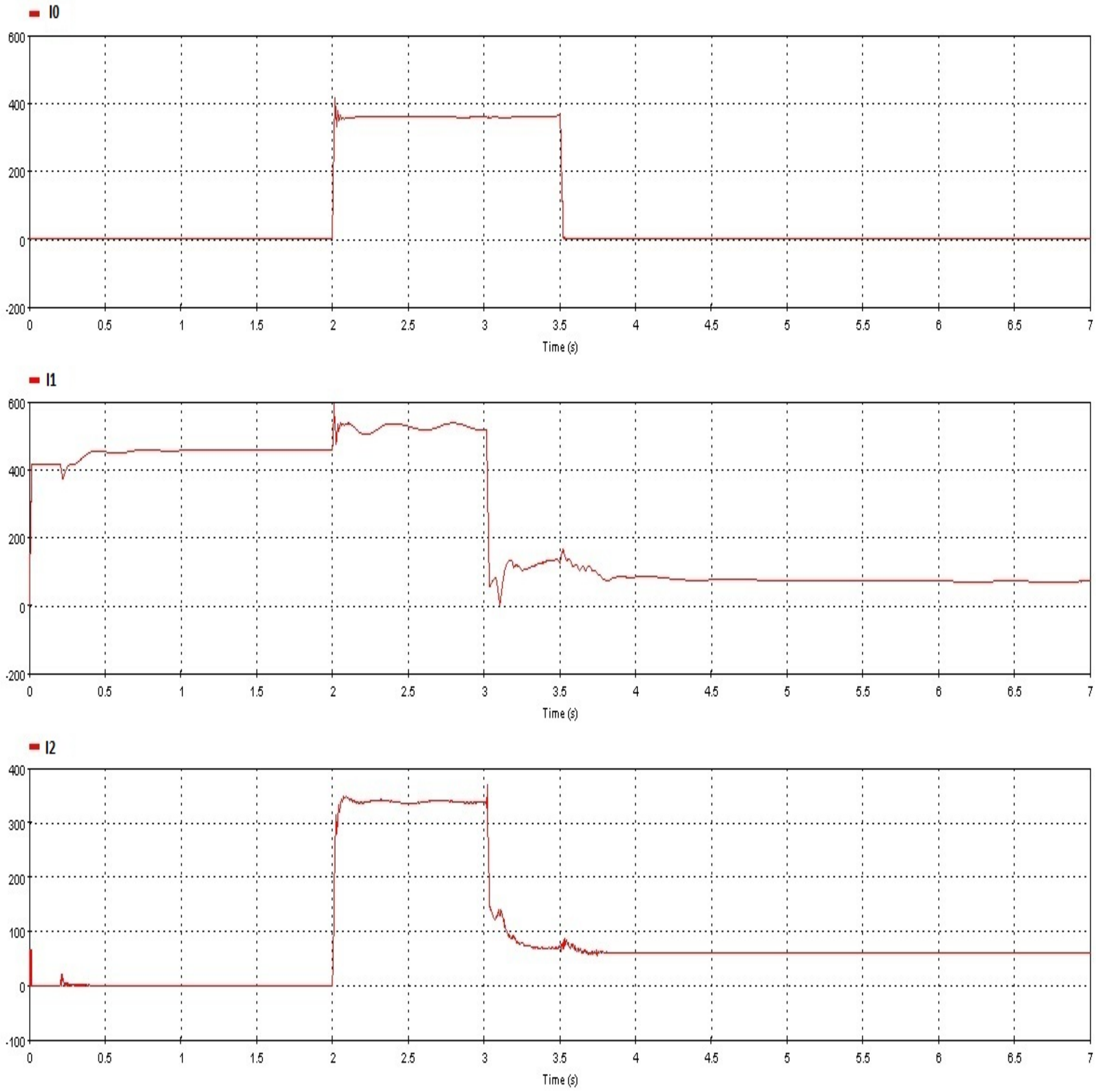

Figure 7.37: Positve, Negative and Zero Sequence Current Under Unbalance Condition

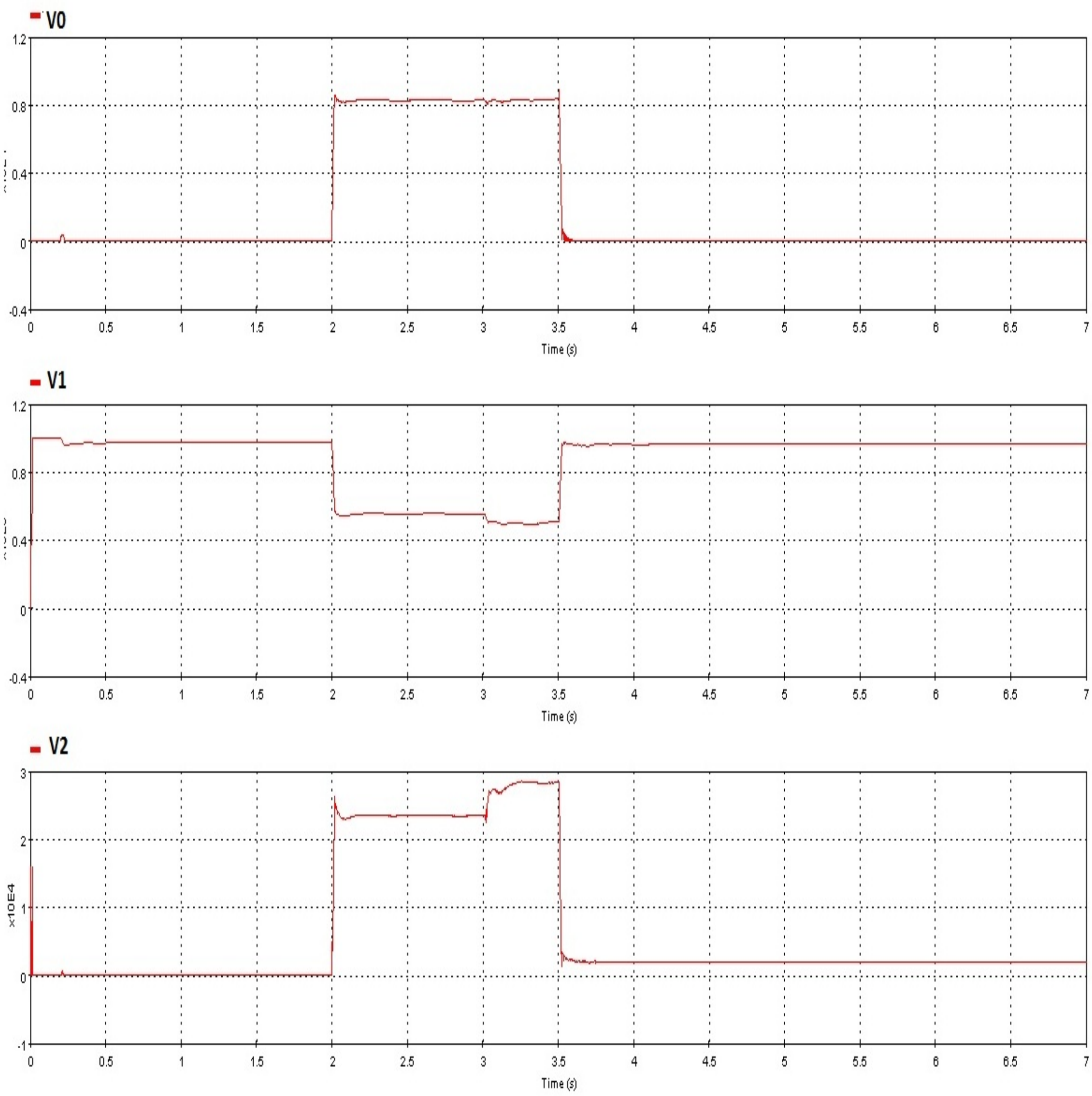

Figure 7.38: Positve, Negative and Zero Sequence Voltage Under Unbalance Condition

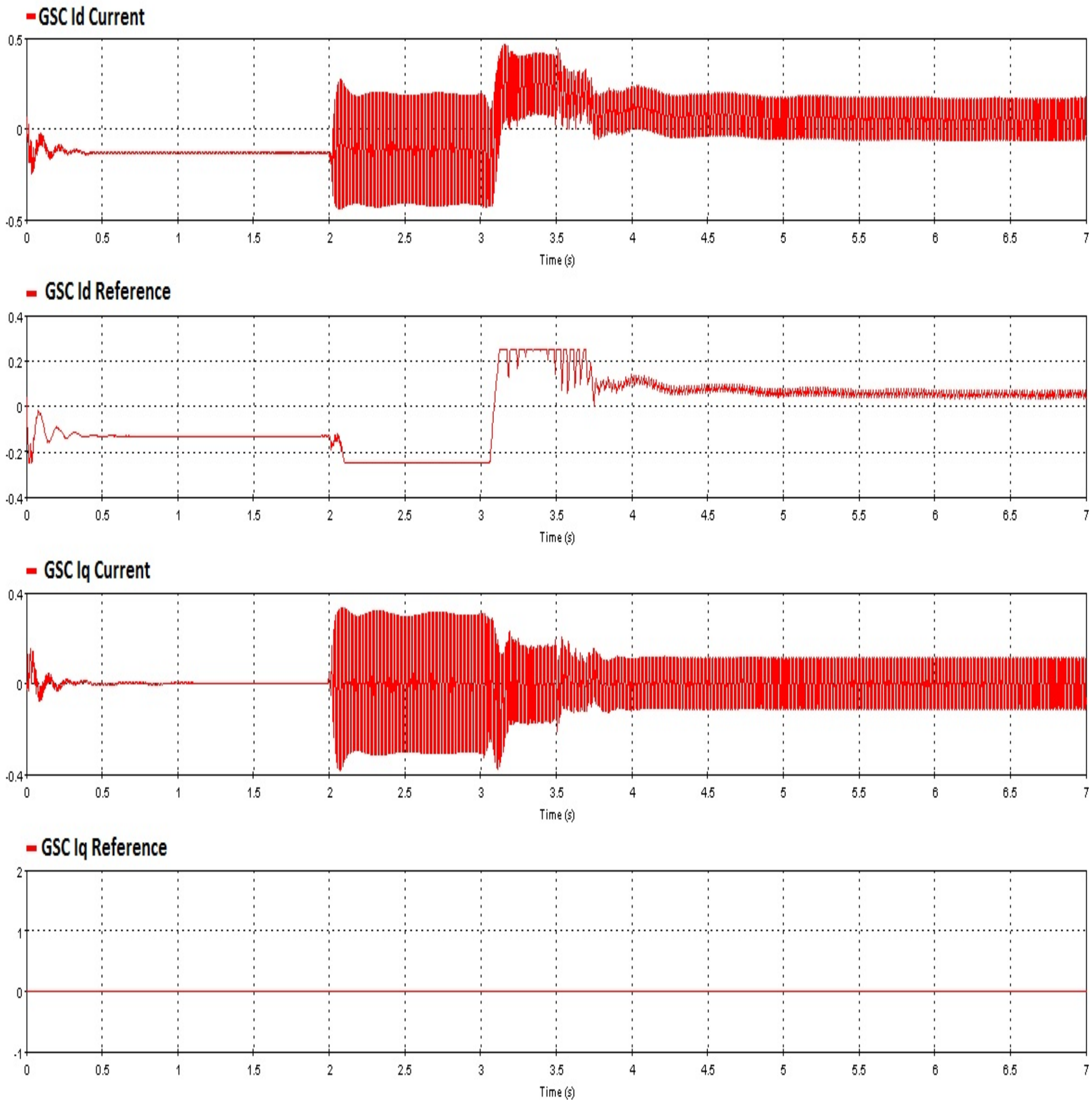

Figure 7.39: Grid Side Converter - Outer Loop Currents

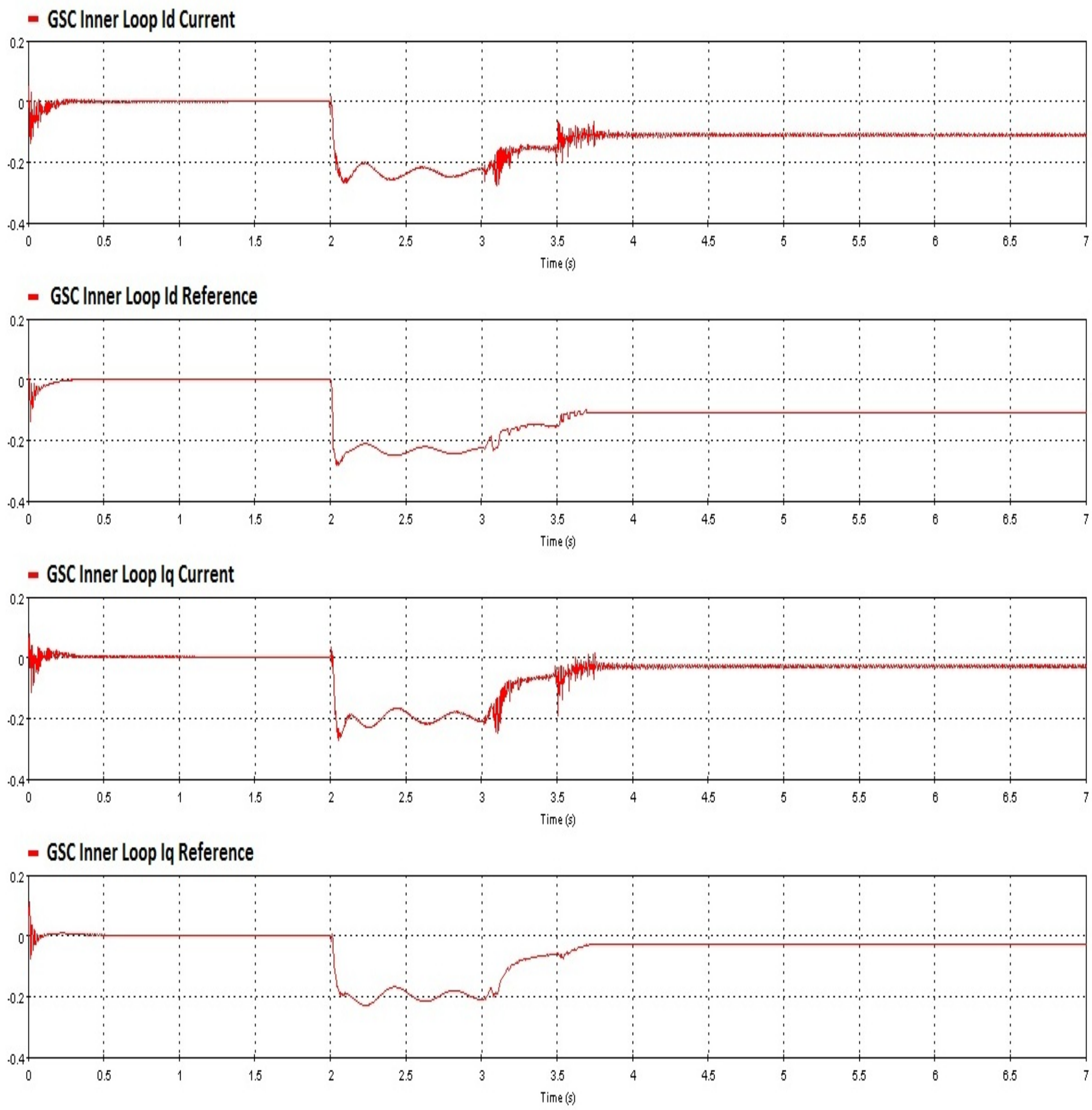

Figure 7.40: Grid Side Converter - Inner Loop Currents

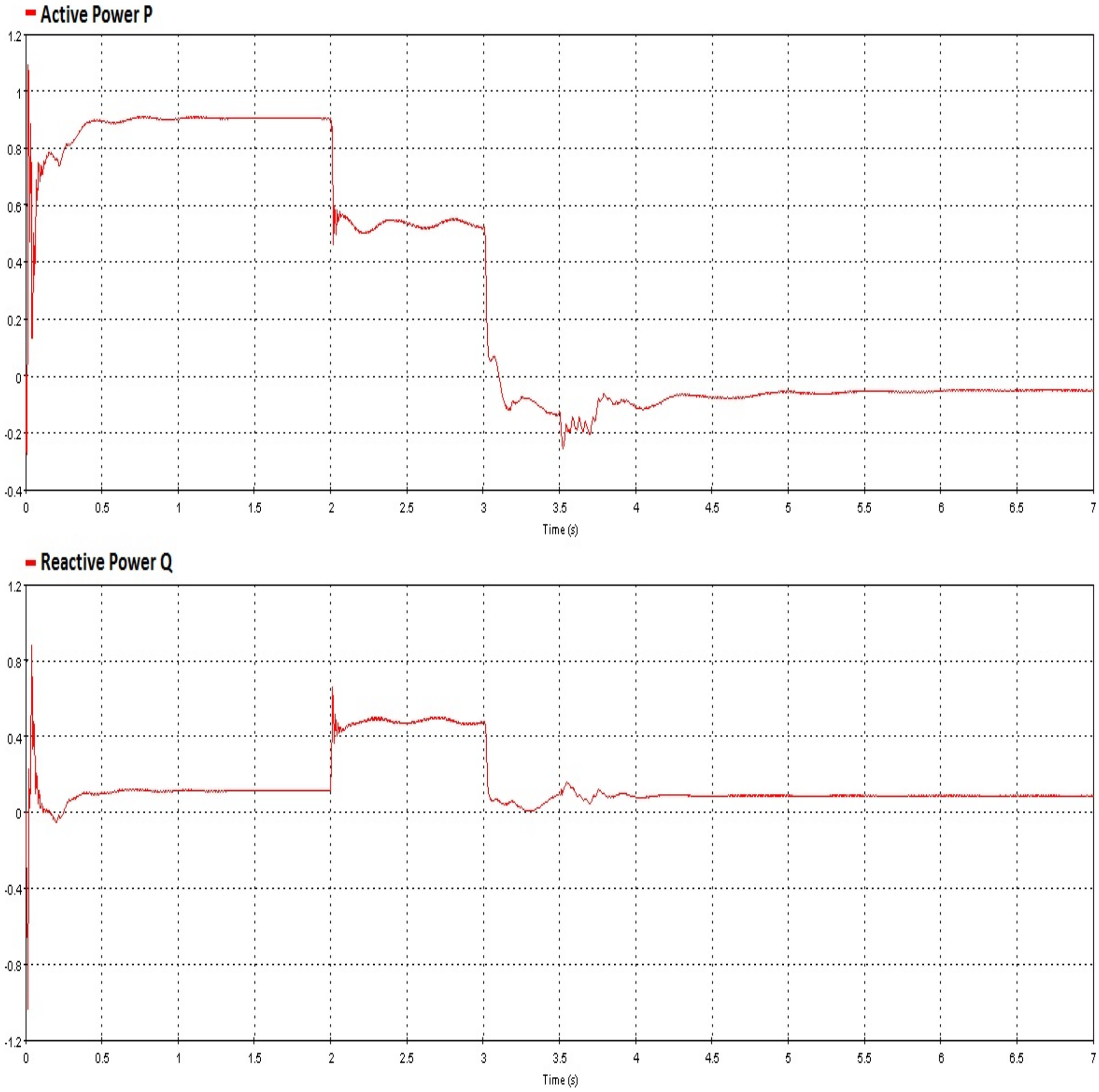

Figure 7.41: Active and Reactive Power of RSC during Fault

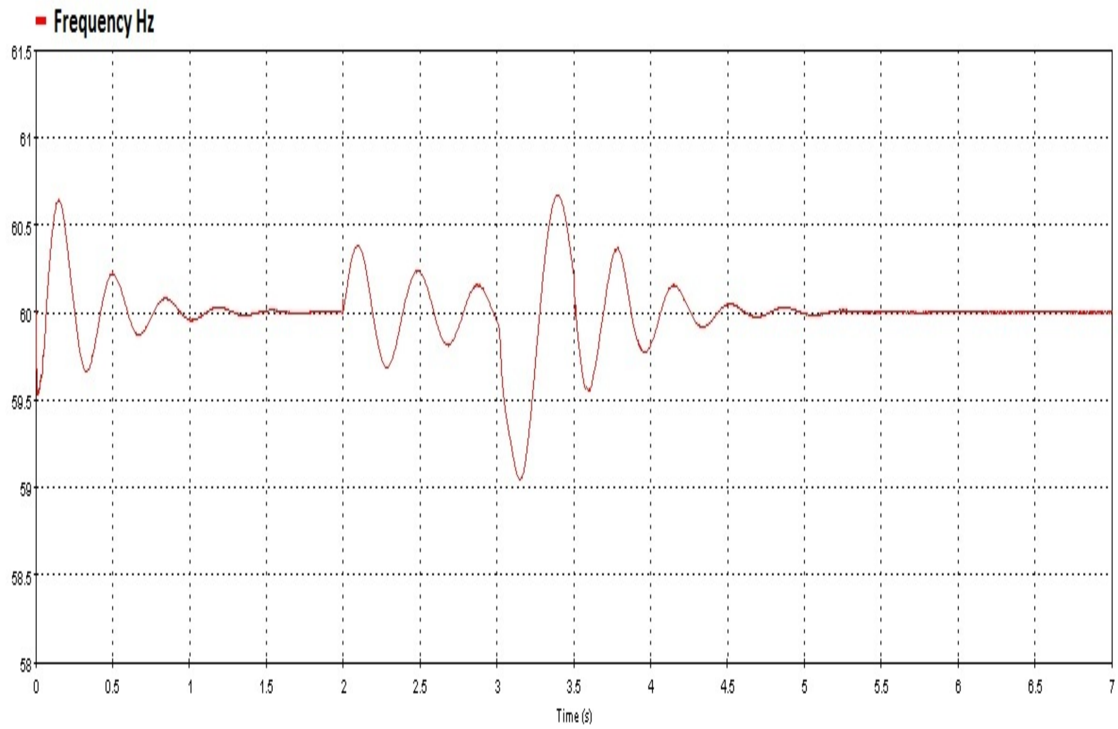

Figure 7.42: Frequency Deviation During Fault

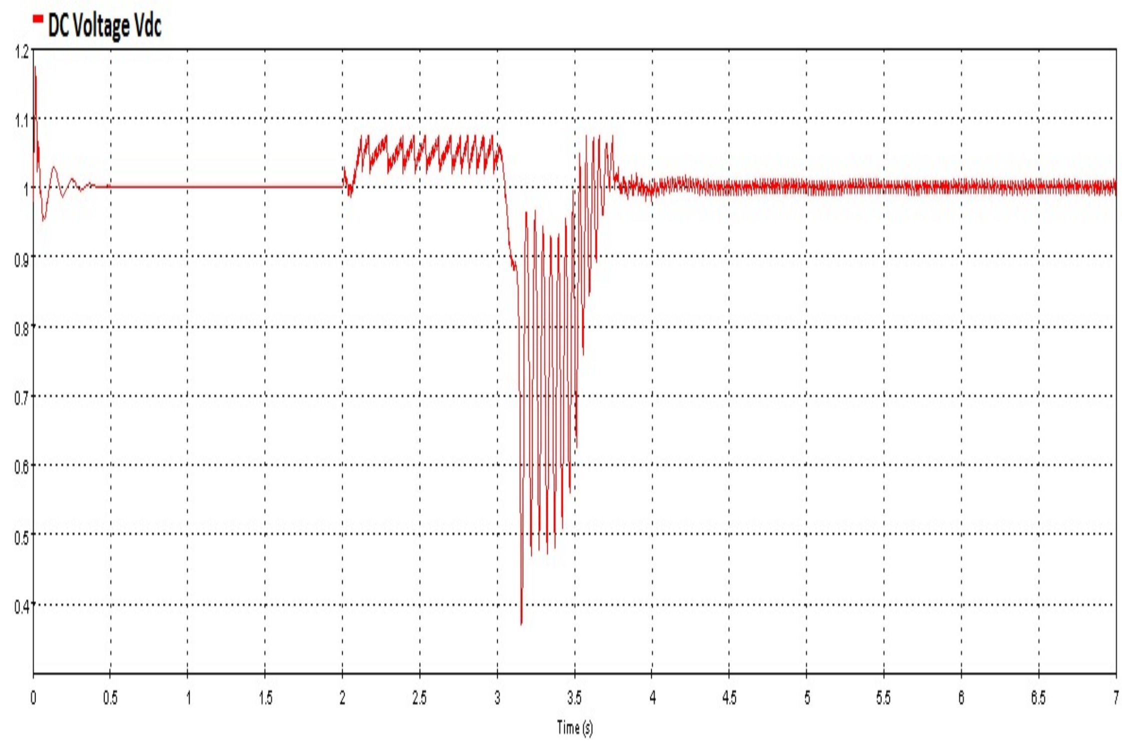

Figure 7.43: DC Link Voltage Deviation due to Fault

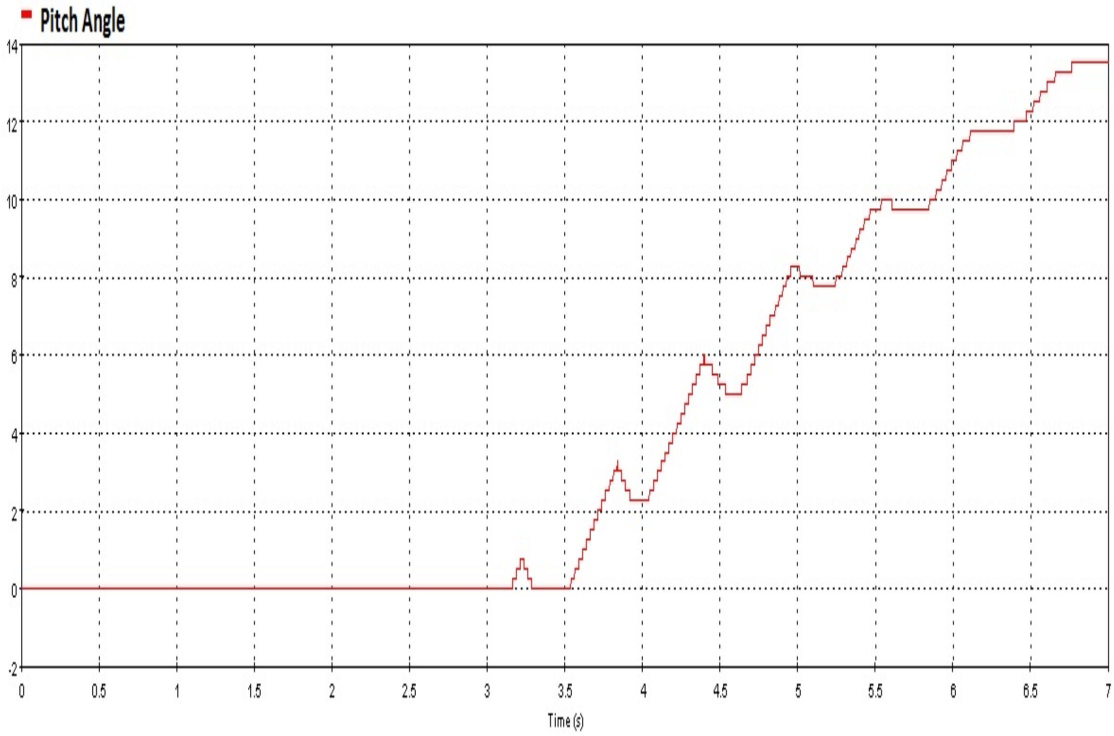

Figure 7.44: Pitch Angle Variation due to Fault

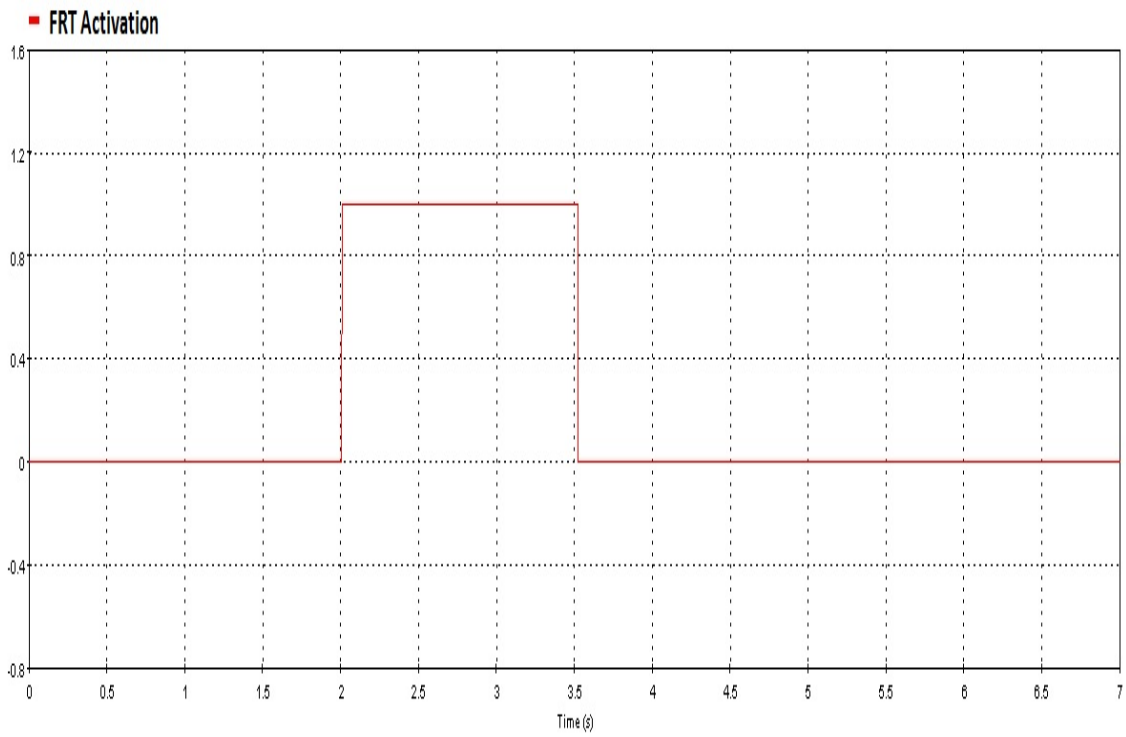

Figure 7.45: Fault Ride Through Activation

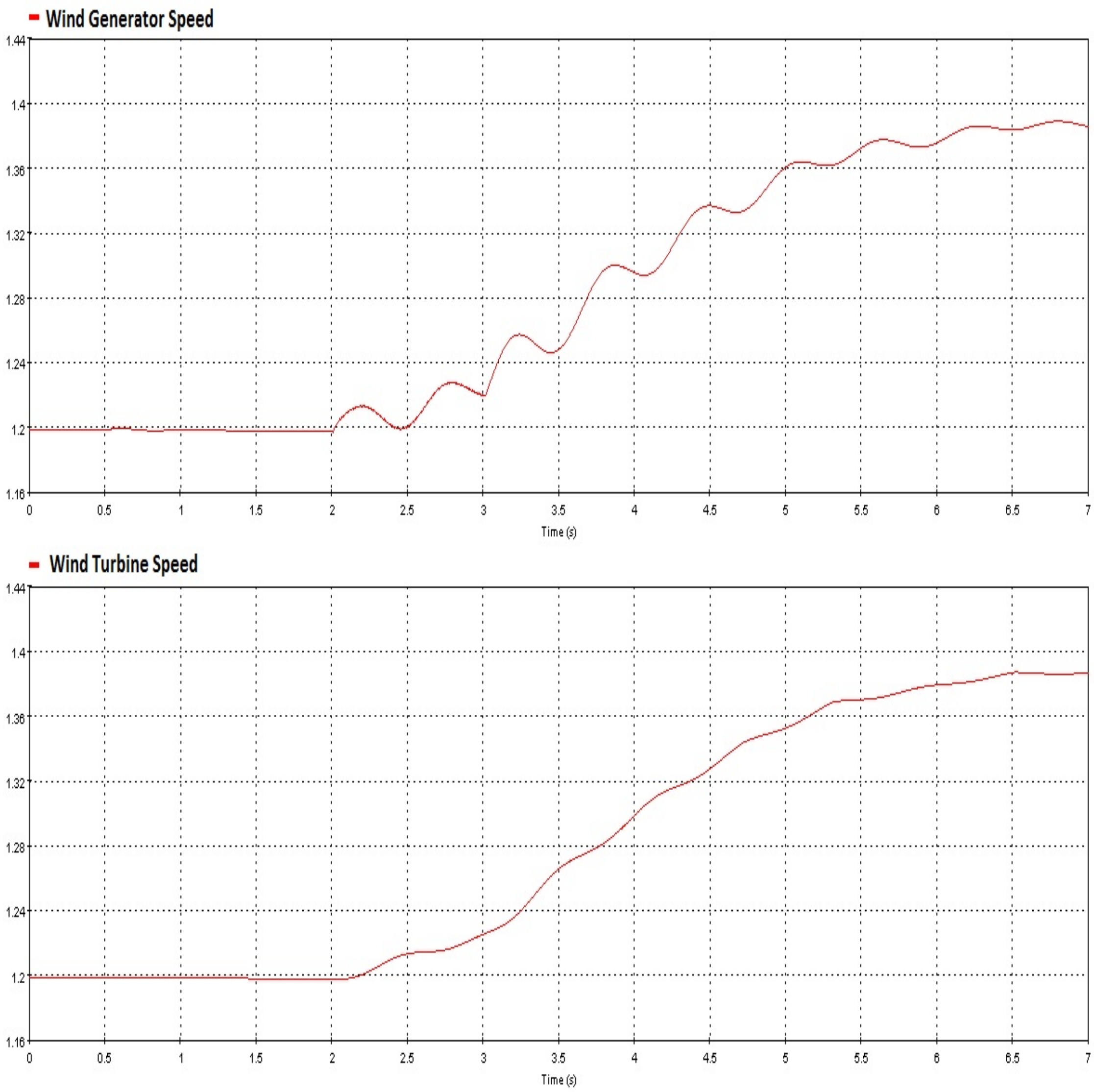

Figure 7.46: Wind Generator and Wind Turbine Speed Deviation during Fault

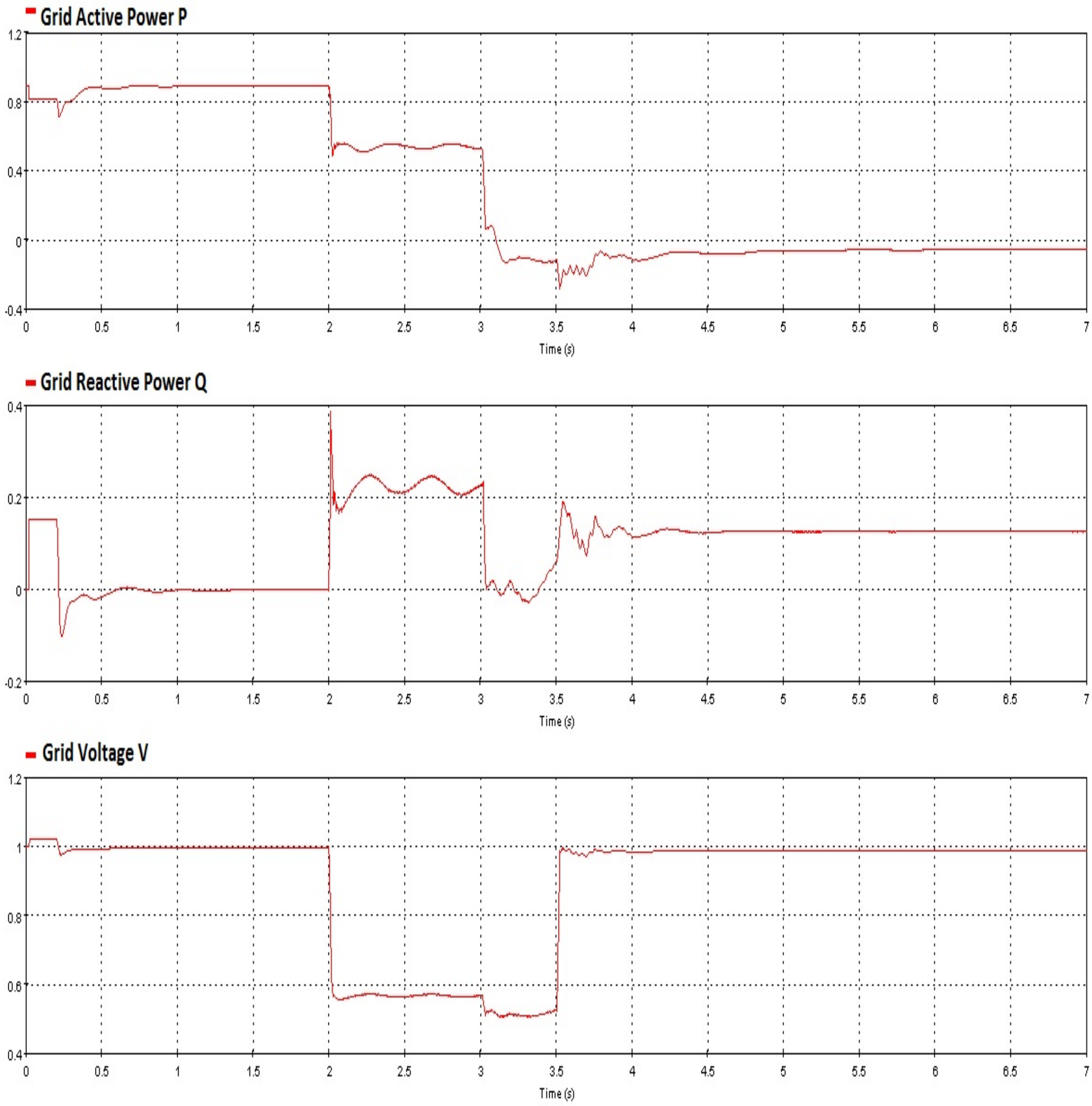

Figure 7.47: Grid Active Power, Reactive Power and Voltage during Fault

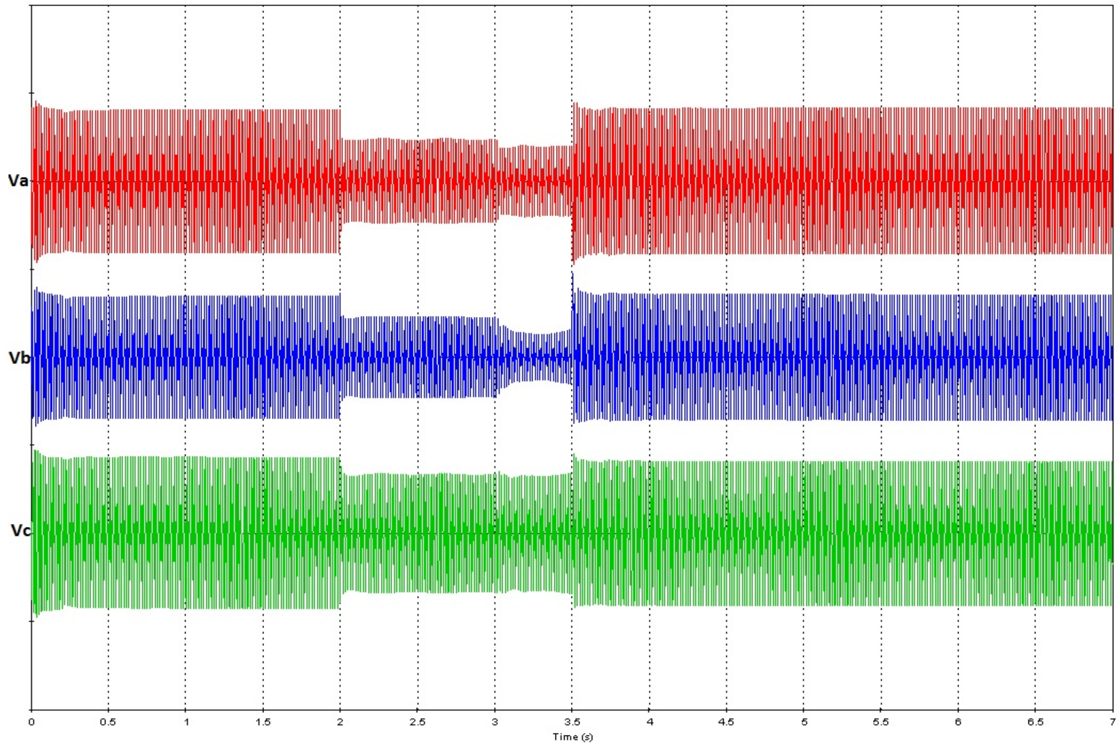

Figure 7.48: Wind Turbine Voltage during Fault

7.11 Conclusion

It is very necessary to survive the fault, through effective Low Voltage Ride Throgh (LVRT) control strategy. LVRT plays and important role in in maintaining voltage stability of a grid-connected wind power system. To observe the grid discipline, grid code is made mandatory requirement to avoid premature tripping of wind generators due to transient and local disturbances, which can further affect the stability of the system and amplify the effect of the grid disturbance. Doubly Fed Induction Generator with partial rated power electronic converters shall have the ability to extract maximum possible power from the wind and shall also have strong FRT capability. Simulation results confirm the fulfilment of LVRT requirement, i.e., the generator remains connected to the grid for low fault time. Generator Rotor Side Converter (RSC) and Grid Side Converter (GSC) control strategies work simultaneously to fulfil the Fault Ride Through (FRT) requirements. The main function of the DC-link capacitor is to store energy and to act as a decoupling between the GSC and RSC so that each can be controlled separately and isolate the wind turbine systems from the grid, which provides protection. It has been observed that the decoupled control strategy is effective in meeting the LVRT requirement.