TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

A
FINAL YEAR PROJECT REPORT
ON

ENHANCEMENT OF FAULT RIDE THROUGH CAPACITY OF GRID CONNECTED INVERTER

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ABSTRACT

Under the demands of contemporary grid code (GC), the solar PV system should stay attached to the grid for a certain time period depending on the voltage sag level under the fault condition. The voltage of the point of common coupling (PCC) is the same when the fault appears on the grid side due to compensation of voltage by the grid connected system. But the output voltage of inverter is very low when fault occurs in the inverter side resulting in a very high DC connection voltage and very high current through the inverter for the power balance. This high voltage of the intermediate circuit can damage the DC link capacitor and high current during the transient fault may damage the inverter.

Moreover, the deflection of the voltage will cause the PV plant to be disconnected from the network based on the modern GCs. But, due to on-growing demand of consumers, it is required to connect the PV system to grid even during faulty condition.

This study proposes a DC Braking chopper approach for the two-stage grid-integrated solar PV system to enhance fault ride through (FRT) capability. The proposed DC Braking control approach consists of a resistor in series with IGBT which absorbs the excess energy in the DC link capacitor during the fault, which will regulate the DC-link overvoltage where required PWM signal for IGBT used in DC braking chopper is generated by the principle of power balance between DC side and AC side. For this work, the algorithm of synchronization evolved to trigger control under the fault. Simulations are carried out using the MATLAB/Simulink software under single phase to ground (LG) fault.

After the use of DC braking chopper, excess energy during single phase to ground fault is absorbed by resistor so that maximum voltage across DC link capacitor falls from 925 V to 665 V and maximum current thorough inverter falls from 774.9 A to 544 A. This ensures capacitor voltage and inverter current doesn’t exceed maximum limit and comes to safer value and ultimately PV system doesn’t disconnect from the grid. Even for the transient fault for 0.2 sec, system becomes stable after the elimination of fault. These results indicate that the proposed DC Braking control scheme can enhance the FRT capability of the system.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	Alternating Current
BC	Braking Chopper
CVT	Constant Voltage Tracking
DC	Direct Current
DCB	DC Braking
FRT	Fault Ride Through
HC	Hill Climbing
IGBT	Insulated Gate Bipolar Transistor
KW	Kilo Watt
LVRT	Low Voltage Ride Through
MATLAB	Matrix Laboratory
MPPT	Maximum Power Point Tracking
NS	Negative Sequence
PCC	Point of Common Coupling
PLL	Phase Locked Loop
P&O	Perturb and observance
PI	Proportional Integral
PS	Positive Sequence
PV	Photovoltaic

CHAPTER ONE

INTRODUCTION

1.1 Background

In recent years, with the rapid rise in demand for renewable energy sources, the PV power generation system is getting major consideration. Consequently the influence of PV systems on grid performance must be studied so that the system meets the grid code requirement and better performance is ensured.

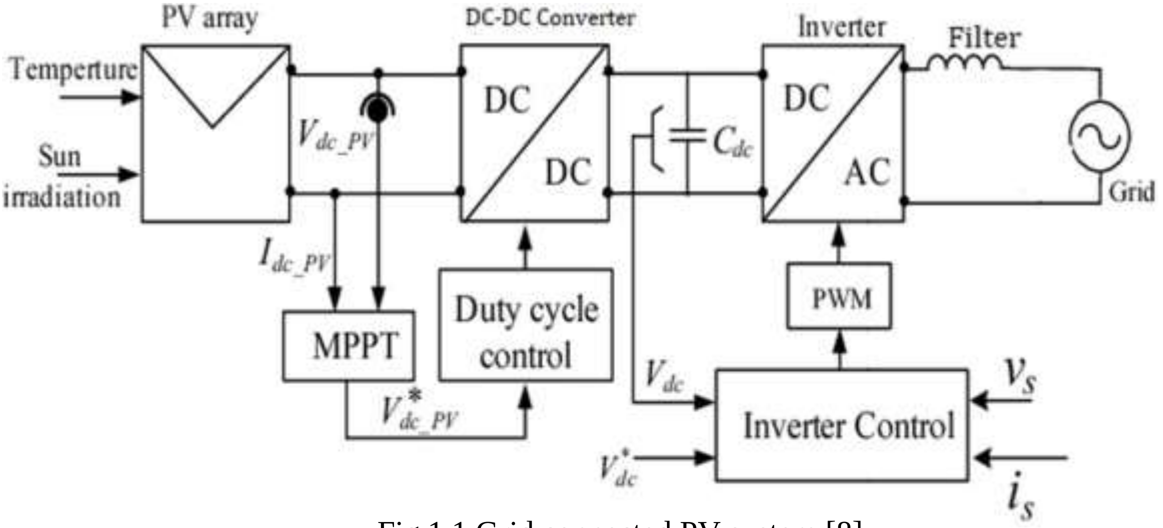


Fig 1.1 Grid connected PV system [8]

Fig.1.1 shows the symbolic diagram of the grid connected PV system. PV array is connected to the inverter through buck boost converter in order to track the utmost power. The inputs to the PV array are temperature and irradiation. For the maximum power tracking, PV output voltage must equal to the voltage that corresponds to the utmost power generated by the PV system. The voltage across PV and current flowing through the PV is sent to MPPT which uses P&O algorithm to generate duty cycle controlling operation of buck boost converter .The voltage produced by the MPPT block is compared with the dc link capacitor voltage which then sent through PI controller to generate the referenced component of current. And then keeping the q component zero as there is no consideration of reactive power, the three-phase current reference is generated using dq- abc conversion.

We have used PLL block to generate the frequency of the grid which is required for dq-abc conversion. The real current and the reference current are contrasted flowing through the inverter to get the pulses for controlling the IGBTs used in the inverter. A grid connected PV system must have Fault Ride Through (FRT) capability when the grid undergoes aberrant circumstance. To understand the FRT, let’s study a Fig 1.2.

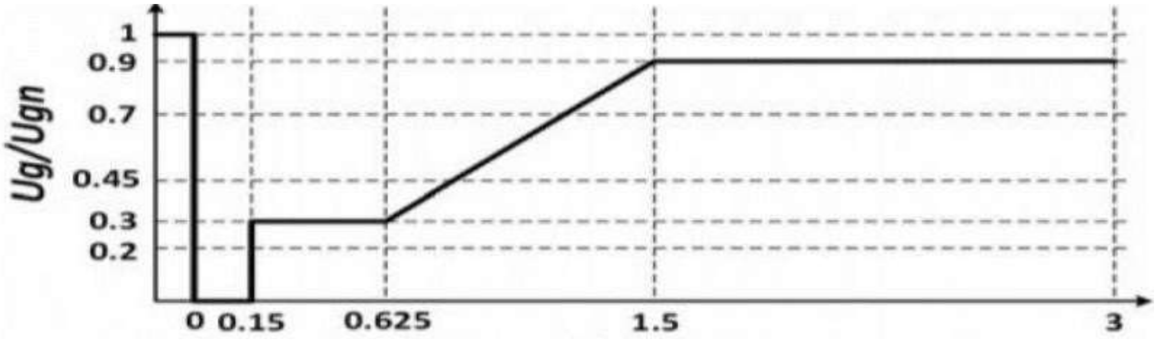


Fig 1.2 FRT Curve (German grid code) [4]

Fig 1.2 shows a typical FRT curve. From this, we can observe that the PV System is to be disconnected from the grid when depth and duration of voltage sag are below the FRT curve. Thus, the ability of producing units and power park modules to ride through faults and disturbances in the super grid transmission system is known as fault ride through. To ensure system security and prevent greater frequency collapse, this is a critical necessity.. For grid-connected PV systems under aberrant circumstance, the FRT control techniques should essentially be as follows:

1) Determine the active and passive current references in the positive (PS) and negative (NS) sequences.

2) Quickly identify voltage issues,

3) Avoid overcurrent failure by restricting current,

4) In two-stage systems, regulate the dc-link voltage and the dc-dc converter.

During any transient fault, voltage sag occurs and for the system to remain linked to the grid, a certain quantity of reactive power must be taken into account by the system according to the voltage sag depth to support grid voltage recovery. When a problem occurs at 400 kV or 275 kV, the main protection is intended to fix it in 80 to 100 milliseconds for a two-ended circuit and often in 140 milliseconds for a three-ended circuit. Since the transmission network's impedance is low, this means that until the problem has been fixed, the voltage seen across the transmission system will also be low. During fault circumstances, each generating unit and power park module must produce the utmost reactive current while staying within the transient rating of the generating unit or power park module, and they must restore active power to 90% of its pre-fault output within 1.5 seconds.

In addition during this kind of fault power imbalance occurs in between input and output side of the buck-boost converter and hence dc-link overshoot occurs. This may cause an exceed in I_{max} of the inverter. So the system is required to have a better corresponding control strategy.

1.1.1 PV system

A Photovoltaic system, a renewable energy power generation technology, is a device which converts solar energy into electrical energy with the help of solar cells. Solar cells are composed of semiconductor materials which have electronic characteristics of PV conversion. PV systems have the features of simple installation, low maintenance, and modularity. The prime technology of the PV system includes control strategy and power electronics technology. The control strategy incorporate MPPT (Maximum Power Point Tracking) while the power electronics technology incorporate the inverter [6].

1.1.2. On grid PV system

An on-grid PV system is one that uses solar photovoltaic harvesters to create electricity and transmit it to electric utilities. An on-grid PV system constantly feeds generation energy to the utility grid. Various parts of a PV system that is attached to the grid include:

1. Photovoltaic modules: There are three kinds of solar cells: amorphous silicon, polycrystalline silicon, and mono crystalline silicon.
2. Junction Box: It is used at the interconnection to the power converter and at a solar PV enclosure where it is used as a bypass diode allowing the power flow from solar panel to utility (Unidirectional).
3. On-grid inverter: It converts the dc power to ac power. It interconnects the PV system with today’s power sector.

4. The main panel and AC disconnect: The main panel and AC disconnect serve to disconnect the DC-AC inverter from the electrical utility grid. The main panel, which separates the PV system from the power grid, is made up of electromechanical elements.

5. Net meter: This device tracks the flow of electricity between an electricity generating system and the utility grid.

6. Electrical grid: This is a network that connects energy suppliers and load centers. [7]

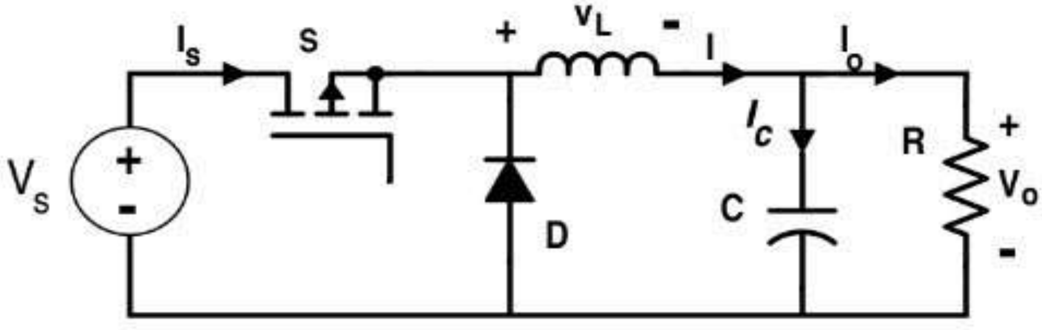


Fig 1.3 Buck-Boost Converter [13]

1.1.3 Buck Boost Converter

The output voltage magnitude of a buck-boost converter, a type of DC-to-DC converter, can be either larger than or less than the input voltage magnitude. It performs both the buck converter's (used for DC voltage step-down) and boost converter's (used for DC voltage step-up) duties, as suggested by its name.

1.1.4 MPPT Algorithm

When MPPT is used, the PV system works at MPP (Maximum Power Point), allowing for the best possible efficiency. There are various methods for the maximum power tracking in PV system. They are Hill climbing method, Perturb and Observation algorithm also the incremental conductance method and many other AI techniques are now used in all areas of electrical engineering. Additionally, the most recent theory in MPPT is the optimal voltage control (OVC).We are going to use the P&O algorithm method to obtain the maximum power point (MPP) in our project.

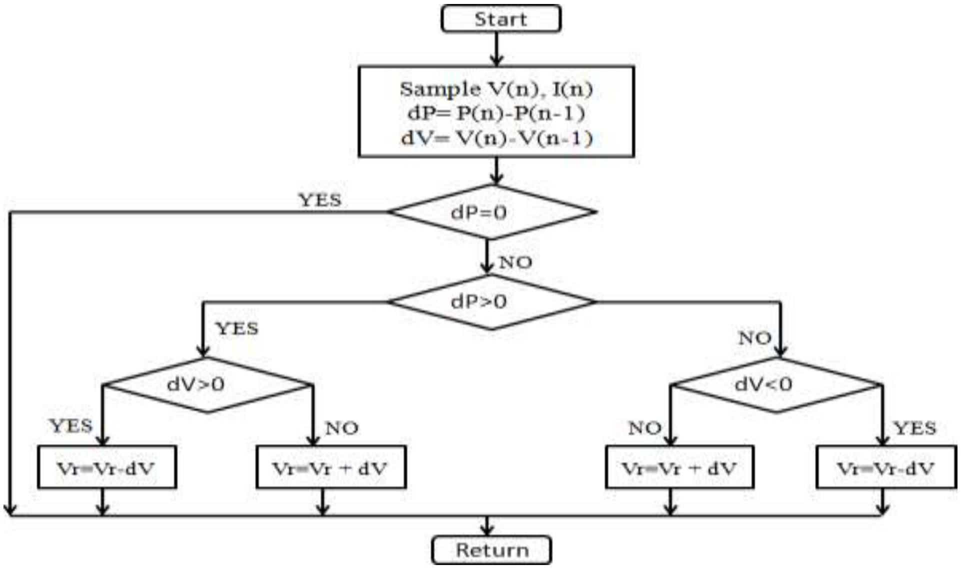


Fig 1.4 Flowchart of P&O MPPT algorithm [1]

Due to their straightforward nature, the Perturb & Observe (P&O) algorithm method is often used in MPPT control. Also the number of parameters to be measured is less. This approach is based on monitoring the output power of a PV array and altering it by altering the current or voltage of the PV array while it is operating. According to the Perturb & Observe (P&O) algorithm, when the PV panel's operational voltage is perturbed by a small amount, if the resulting change in power, P, is positive, then we are moving in the direction

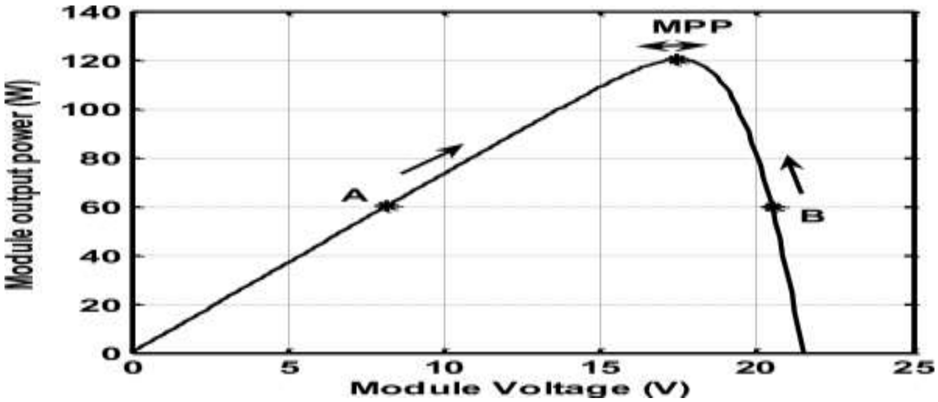


Fig 1.5 MPPT algorithm curve [13]

of the MPP and we continue perturbing in the same way. If P is negative, we are moving against the MPP and must alter the provided perturbation's sign.

1.1.4 DC Braking Chopper

Whenever there is increase dc-link voltage above a certain threshold, dc-link brake chopper, a simple safety measure, shorts the dc-link by means of a power resistor. The brake is employed to accept transitory rotor overcurrent while controlling the dc-link voltage. The rectifier (IGBT) crowbar design and the dc-link brake have certain similarities. Instead of a separate rectifier, there are six antiparallel diodes in the rotor-side converter of the DFIG which are modified to care about the short-circuit currents. There is a power resistor and series switch which is connected in parallel with the dc link capacitor to drain power as required. The components of a DC braking chopper include braking resistance and a PWM signal generation circuit that employs a PI controller to control an IGBT device while it is malfunctioning.

1.1.5 Hysteresis Band current controller

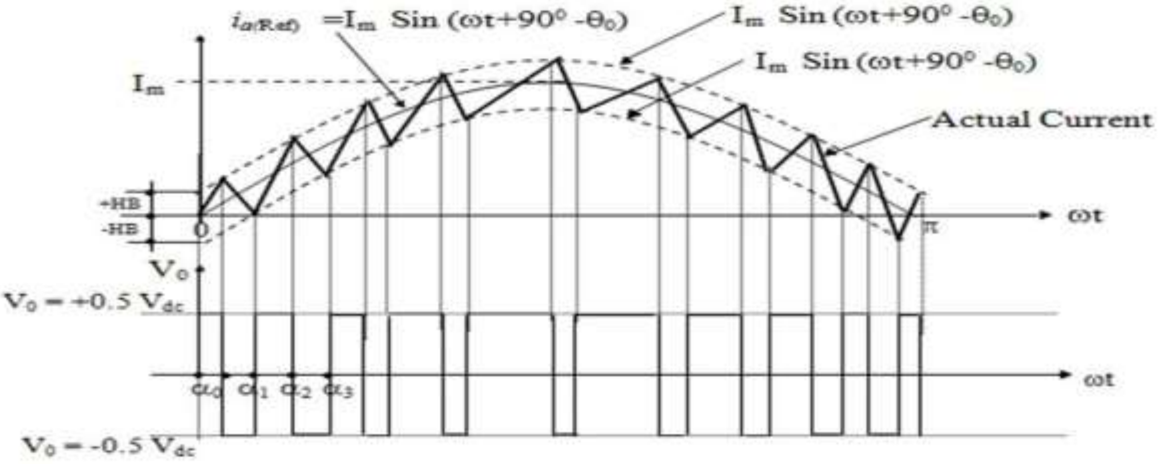


Fig 1.6 Hysteresis Band Current Controller [13]

- The controller compares the reference current generated (iref) and the instantaneous injected current (io) from the inverter as input in the block, and the hysteresis band of the current is subsequently established.
- When the T1 is turned ON, the current (i_0) builds up through an inductive circuit (L_0 R_0), when it hits the upper band, T1 turns Off and T2 turns On.

- When the T2 is turned ON, the current (i_0) decays through inductive circuit (L_0 R_0), when it hits the lower band, T2 turns Off and T1 turns On and so on and accordingly PWM gate signal is generated for phase-a and the inverter currents tracks the Ref current.
- Similarly, the gate signal for phase b and phase c is generated.

1.2 Problem Statement

- During the transient fault, the PV may get disconnected from the grid.
- DC-link voltage may fluctuate due to lack of control strategy under grid voltage fault.
- Fault in grid can cause overshoot in grid current which may cause exceed in maximum current (I_{max}) of inverter and can damage it.
- Frequency fluctuations for sudden change in active power by loads.
- Harmonic distortion is a significant power quality issue which may occur due to the use of power inverters
- PV systems are disconnected from the grid, which results in end users experiencing a power shortage.

1.3. Objective

- To develop a Simulation model of Grid-connected PV system with LVRT control strategy using hybrid approach so that PV system can continue to supply the power to grid even during transient fault period.

1.4 Scope and limitations

The scope of the project can be viewed from technical, regulatory and economical aspects. Like In technical aspect, its scope involves improving design and control strategies of the inverters. This includes using advanced power electronic devices and control algorithms to improve the inverter response to fault. And in regulatory scope, it involves the setting standards and guidelines for FRT performance as well as ensuring compliances with the standards set by the grid code. And in economic scope, it involves assessing the cost effectiveness of the enhanced FRT capability including the cost of implementing the technology, the benefits to the grid and the potential revenue streams. In conclusion, enhancing the FRT capacity of grid-connected inverters is essential for improving the stability and reliability of modern power systems.

Limitations of this project can be its cost. The cost of enhancing the FRT capacity of grid-connected inverters can be significant. This can include the cost of upgrading the inverter hardware, implementing new control algorithms, and testing and validation of the enhanced FRT capability. These costs may be passed on to the end-users, which could impact the economic feasibility of the enhanced FRT capability. Also, there can be technical limitations including compatibility issues with existing grid infrastructure, thermal limitations, and voltage and current rating limitations. There may be regulatory challenges in implementing enhanced FRT capability due to the lack of standardized regulations across different countries and regions. Different regulatory requirements could lead to varying levels of FRT capability and limit interoperability.

Implementing enhanced FRT capability can introduce operational challenges such as increased maintenance and monitoring requirements, and additional complexity in the control and operation of the grid-connected inverters. Also, DC braking chopper adds the additional losses to the inverter system which reduces the overall efficiency of the system. Likewise, DC braking choppers may not be compatible with certain types of grid connected inverters which can limit their usefulness in certain applications.

In conclusion, while enhancing the FRT capacity of grid-connected inverters offers significant benefits, there are limitations and challenges that need to be considered, including cost, technical challenges, interoperability, regulatory challenges, and operational challenges. Overcoming these limitations and challenges requires collaboration between manufacturers, regulators, and grid operators.

1.5 Project Outline

The project consists of following chapters:

- The project consists of a total of five chapters including this chapter.
- This chapter, which is the first chapter, explains about the grid code requirements, FRT control strategies and its importance, and the components of an on-grid PV system. The chapter also contains problem statements, objectives of the project along with its scope and limitations.

- The second chapter provides literature review on many research papers, articles, publications and books from major publishers to study and analyze the requirements and findings from previously held similar research and their results.
- Chapter three provides the methodology used for the simulation of grid connected PV systems with and without control strategies and comparing their responses in case of unsymmetrical fault in the system.
- Chapter four explains the results of the simulation of the control strategies used in grid connected PV systems and discusses the results obtained.
- Chapter five concludes the project and its findings along with recommendations on what more can be done to take the project's result to higher accuracy.

CHAPTER TWO

LITERATURE REVIEW

2.1 Review of paper

Recently, the FAULT RIDE THROUGH (FRT) capability in grid-connected PV Systems has been the subject of much study. Incorporating FRT capability into large-scale PV is the focus of numerous works in order to prevent trip-off during system disturbances. Current-limiting droop control methods have been used for FRT enhancement which, in order to support the grid voltage, only boosts reactive power, while real power immediately declines due to the intrinsic current-limiting feature [1].

Fuzzy based real and reactive power control methods have been used to enhance the FRT capability of PV systems. It displays a modified inverter real and reactive power control technique based on fuzzy logic that may be used to reduce active power flow in the grid and inject reactive current to stabilize the grid voltage. [2].

Secondary control methods have been applied to improve fault ride through capability which use a droop control method to inject reactive and active power to the grid according to their droop gain. Also, a delayed signal cancellation (DSC) algorithm has been applied which ensures the compensation of the positive sequence component and cancellation of negative and zero sequence components. The analysis of positive, negative and zero sequence components seems to be difficult in this project. [3].

A-MPPT (Avoiding MPPT) strategy is used to enhance the FRT capability of inverters The two modes can be switched by transferring from MPPT manner to voltage regulator manner and back using a voltage relay. But by doing so, maximum power is not delivered to the grid during A-MPPT (Voltage regulation mode) operation and only regulates the DC link voltage. [8].

Similarly, there are different techniques to enhance the FRT capability of grid connected inverters published in different papers. But the techniques described in those papers focus on the grid side fault and prevent the voltage sag occurring at point of common coupling.

So, we have proposed a system which includes a two-stage photovoltaic system, tested for FRT operation by adding a DC braking chopper at the DC-link of the inverter to regulate the overshoot in DC-link voltage and minimize the overcurrent through the inverter [4].

CHAPTER THREE

METHODOLOGY

3.1 Overview

The simulation of the project will be performed in MATLAB. We will adopt the following steps to achieve the objectives of our project:

1. Theories related to PV-Panel, DC-DC Boost converter, MPPT algorithm, 3-phase inverter, line filter, fault ride through capability and Dc braking chopper will be studied.
2. Simulation model of grid connected PV system with MPPT logic and without DC braking chopper will be developed.
3. Performance of the above system will be observed in case of transient unsymmetrical fault.
4. Simulation model of grid connected PV system with MPPT logic and with DC braking chopper will be developed.
5. Performance of the final system will be observed in case of unsymmetrical fault and the results will be compared with previous one.

3.2 Block diagram of proposed system:

The suggested system uses a hybrid strategy that includes a DC brake chopper to increase the capacity of grid-connected inverters to survive the fault ride through.

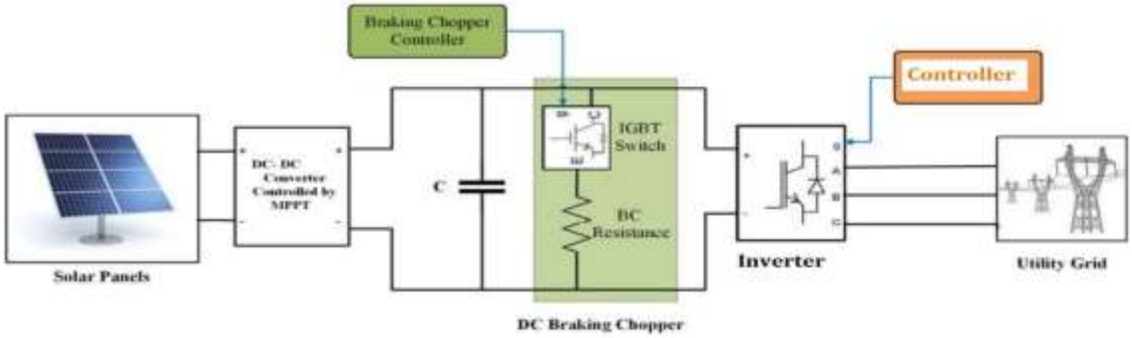


Fig 3.1 Block Diagram of Proposed system [8]

The suggested system's block diagram, which includes a DC brake chopper connected in parallel to the DC link capacitor, is shown in Fig. 3.1. A resistor connected in line with an IGBT makes up the DC brake chopper, which absorbs extra energy from the DC link capacitor during a breakdown to control the DC-link overvoltage and safeguard it from harm.

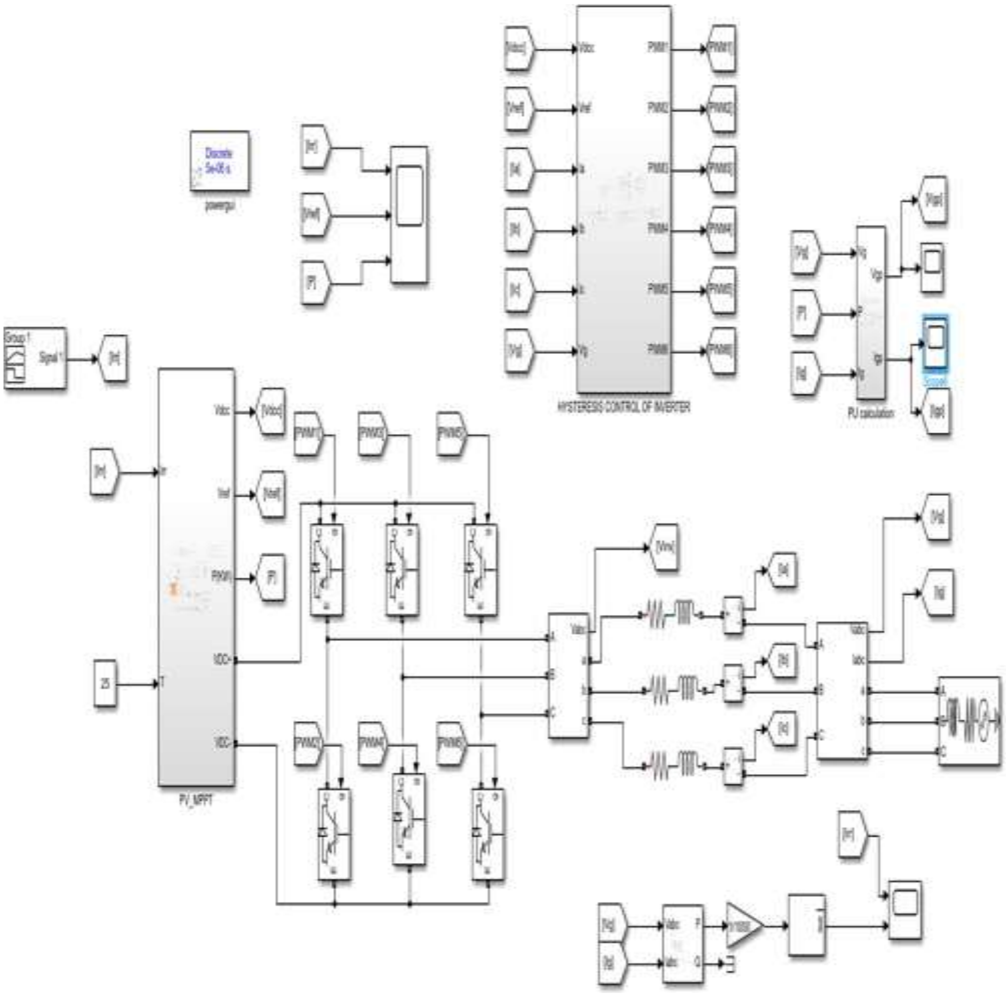


Fig 3.2 Simulation of PV system

3.3 Simulation Model of PV System

The simulation model of a 50 KW grid-connected PV system is shown in Fig. 3.2. 17 numbers of series strings and 18 numbers of parallel strings of array modules are used to design a 50 KW grid connected PV system. Maximum Power Point Tracking (MPPT) method is used to extract the maximum power from the PV system which is fed into a Power inverter that inverts the DC power into AC Power. Output from the inverter is not pure sinusoidal, so by using an inductor filter the harmonic component of non-sinusoidal power is converted into pure sinusoidal power. Since no practical filters are purely inductor, the combination of resistance and inductor is used to accommodate with practical filter. Then it is finally connected to the grid operating at 400V.

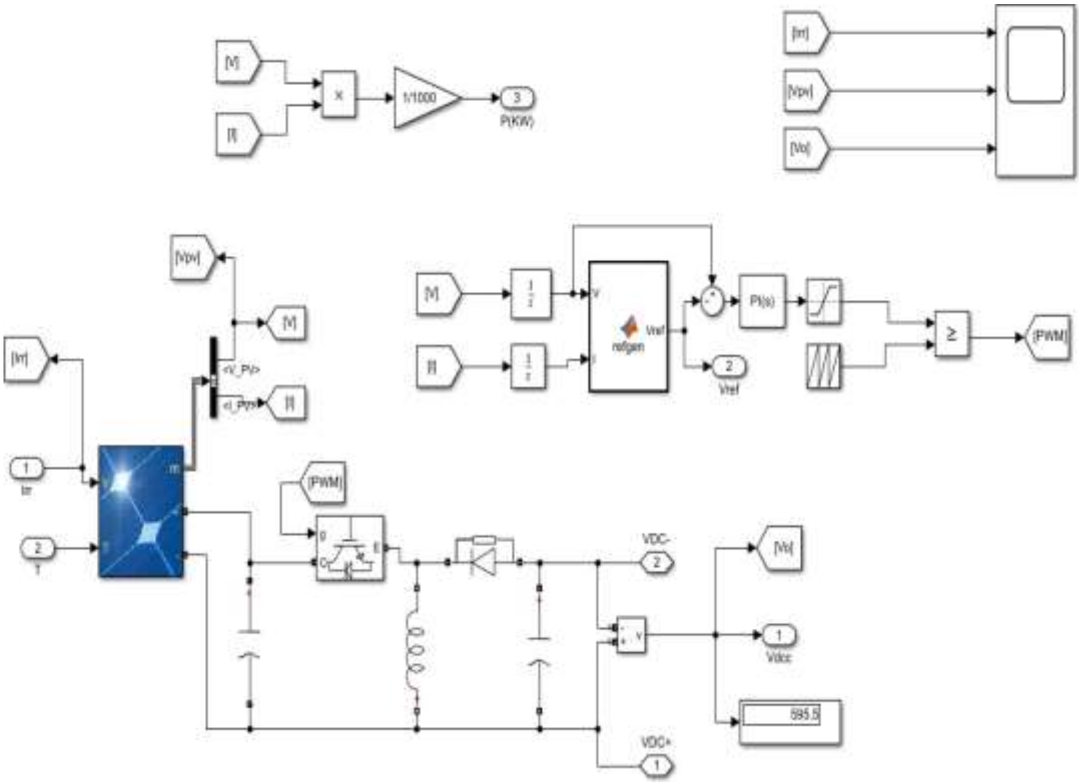


Fig 3.3 Simulation model of PV MPPT subsystem

3.4. PV MPPT Subsystem

Since natural output voltage from a PV system may not be equal to the voltage that corresponds to maximum power, buck-boost converter is used to step up the voltage that corresponds to maximum power. MPPT method is used to generate the PWM signal that is required for the IGBT used in buck-boost converters. By properly tuning the value of inductor and capacitors, input and output voltage from the buck-boost converter is able to track the voltage that corresponds to maximum power that means maximum power from the PV system is available to the inverter.

3.5 Hysteresis current control logic of inverter

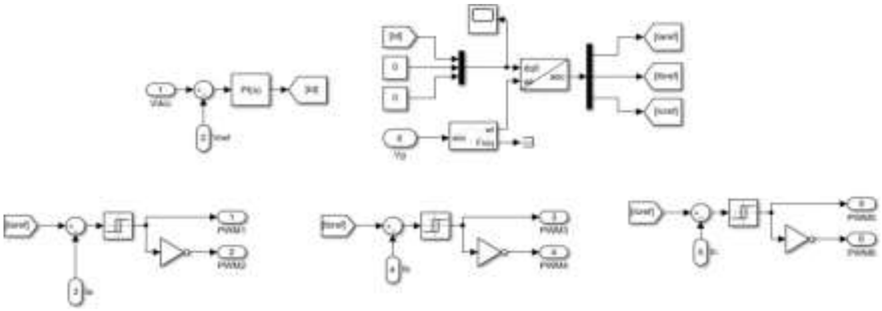


Fig 3.4 Hysteresis current control logic of inverter

In order to transfer the maximum power to the grid, the voltage across the DC link capacitor must be constant which can be done by proper switching of IGBTs used in the inverter. If the switching of switches of the inverter is not done properly, there is either a rise or fall of voltage of the DC link capacitor. If the capacitor voltage is increased, it is assumed that the capacitor stores the charges supplied by the PV system and utmost power is not transferred to the grid side such that grid side AC power is less than the utmost power that a PV system can supply. Similarly if the capacitor voltage is decreased, it is assumed that the capacitor discharges itself and grid side power is found to be greater than the maximum power that a PV system can supply. So to control the inverter, Hysteresis current control logic is used. Reference currents required for each phase is generated by dq0 to abc block where direct axis current is generated by comparing the reference voltage generated by MPPT and actual voltage appears at output of buck-boost converter and angle information of grid is provided by Phase locked loop (PLL) block. To create the PWM signal required for IGBTs of each phase of inverters, reference current of each phase is compared with actual current and fed to the hysteresis relay. Hysteresis relays are switched between 5A to -5A band. If the band of hysteresis relay is kept too small, switching of IGBTs is very fast enough which is practically not possible and losses will increase significantly. So to minimize losses and to meet the practical requirements, hysteresis relay with proper band is selected.

3.6 Simulation model of grid connected PV system with single phase to ground fault

In normal conditions, the total maximum power transferred by the source is equal to the power accepted by the grid and voltage drop between the grid and PV source. The value of voltage drop is usually small during normal conditions.

But when the fault occurs (line to ground fault in our case), the maximum power transferred from PV source at every instant but the power accepting capacity of the grid is very less. So the surplus energy is dropped in the dc link capacitor so that the voltage of the dc link capacitor and the value of current in the inverter increase drastically. Due to overvoltage, the dc link capacitor over-stressed as well as due to over current the inverter may damage.

Such types of problems faced by PV systems during fault conditions due to which the PV system may disconnect from the grid which will make the grid more unstable.

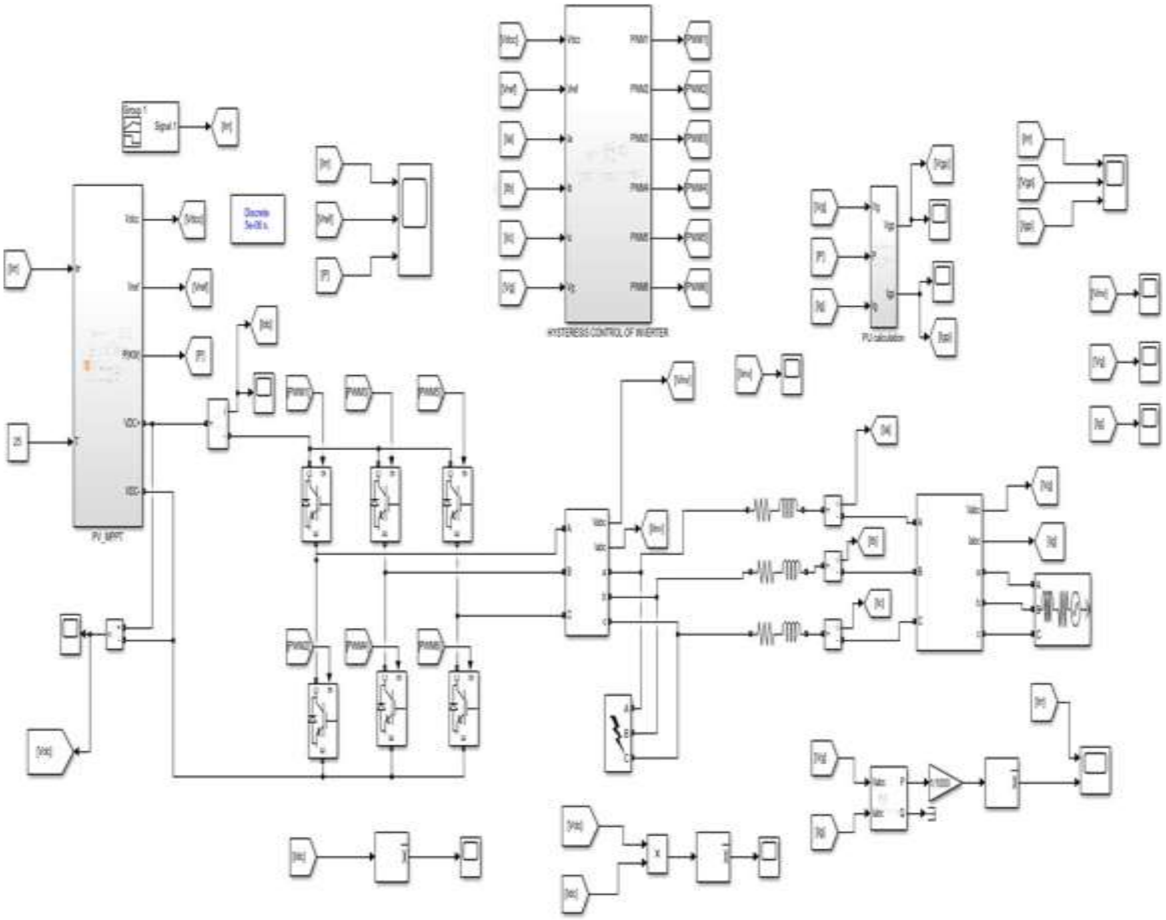


Fig 3.5 Simulation of PV system with phase to ground fault

3.7 Grid-connected PV system simulation model with DC Braking Chopper

- Observed the transient fault on a 50 KW grid connected PV System on the inverter side.
- Developed a simulation model of a 50 KW grid connected PV system with LVRT control strategy using DC Braking chopper to enhance the Fault Ride Through capacity of grid connected inverter.

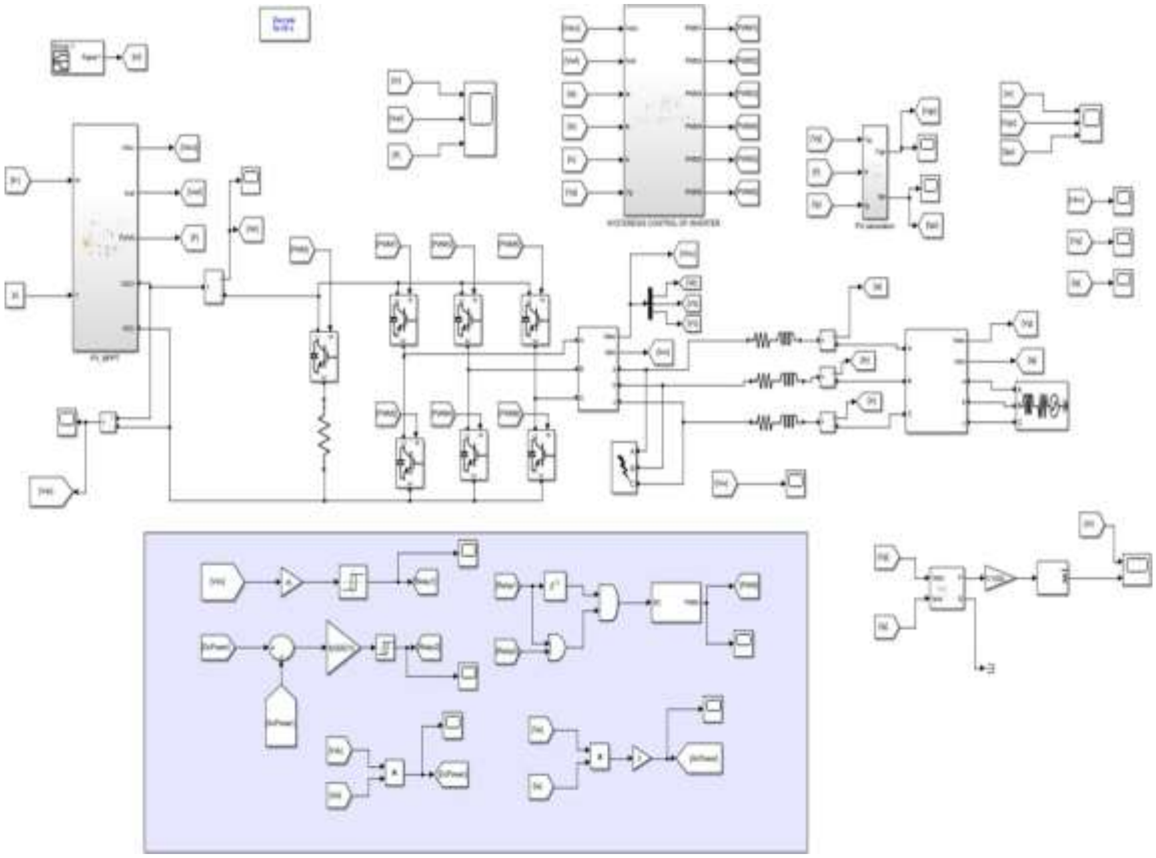


Fig 3.6 Simulation of grid connected PV system with DC Braking Chopper

3.8 Working mechanism of DC braking chopper control scheme

The IGBT present in the DC braking chopper is switched on as soon as it senses any fault situation. Then, the resistor in the DC chopper absorbs a surplus amount of energy. The DC connection voltage is retained on the grid having range specified by the stimulation and stoppage voltage. When the chopper gets to the preset upper limit, it gets activated and the chopper is shutdown when DC link voltage gets to the preset lower limit [4].

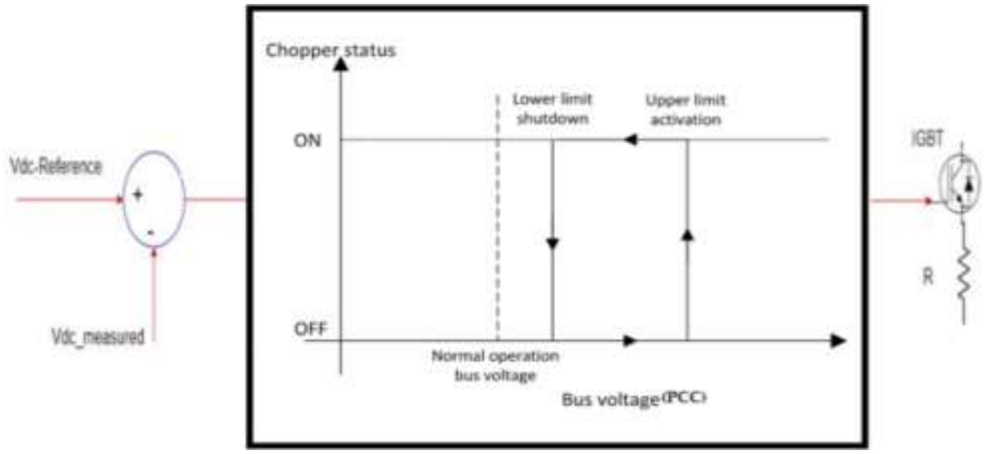


Fig 3.7 DC Braking chopper (DBC) controller [4]

In other words, when the dc link voltage rises above a certain threshold, the DC-link brake chopper, a simple protective device, shorts the dc link along a power resistor. As shown in Fig. 3, a power resistor is connected in parallel with the DC-link capacitance and in series with a switch to provide power sinking as required.. An anti-parallel diode could be placed across the braking resistor to take into account the effects of stray inductance when the chopper IGBT is turned off.

The switch of the brake Chopper will be activated during the grid voltage decrease as a result of the DC-link voltage spike. The power is sinked through the resistor to avoid a unsafe over-voltage occurrence across the DC-link capacitor. The voltage across the brake resistor will be nearly constant. Consequently, the brake resistor can be thought of as a roughly constant load, sinking power in accordance with [9].

$$P_{brake} = V^2_{dc} / R_{brake} \qquad [9]$$

The least amount of current will be used by a DC brake resistor of suitable size. The maximum current carrying capacity of the resistor and IGBT pair, which is established by the permitted upper limit of DC link voltage, determines the minimum resistance necessary.

$$I_{brake} < V_{dc,brake} / R_{brake} \qquad [11]$$

For the dc connection to be protected from the worst case, the braking resistor needs to have a high enough rating. The DC-link capacitance needs to be rated to tolerate these over currents in rectified form. The amount of the overvoltage determines the duty cycle at which the chopper control circuit switches the IGBT device. As the voltage increases until it reaches its maximum permanently on state, the duty cycle of the chopper increases. As soon as the dc voltage falls below a decreased hysteresis threshold level, the DC braking resistor disengages on its own [10]. As shown in Fig.3.3The BC is managed by two open control loops. After the first detects a rise in voltage (the utmost DC voltage the DC-Link capacitor could hold out against, or 120 percent of the DC-Link voltage specified), by placing the braking chopper resistor across the DC-Link capacitor, and the IGBT is activated. The second technique turns off the IGBT when the DC-Link voltage collapse below the predetermined threshold, such as 90 percent of the estimated DC-Link voltage Because of the previous voltage relay pick up and release settings, which result in the IGBT's frequent ON-OFF switching, the DC voltage varies.. By employing the 2nd loop to discover the power imbalance amid the Direct Current side and the Alternating current side for a predetermined amount of time, the BC chopper is kept on for a while.[8].

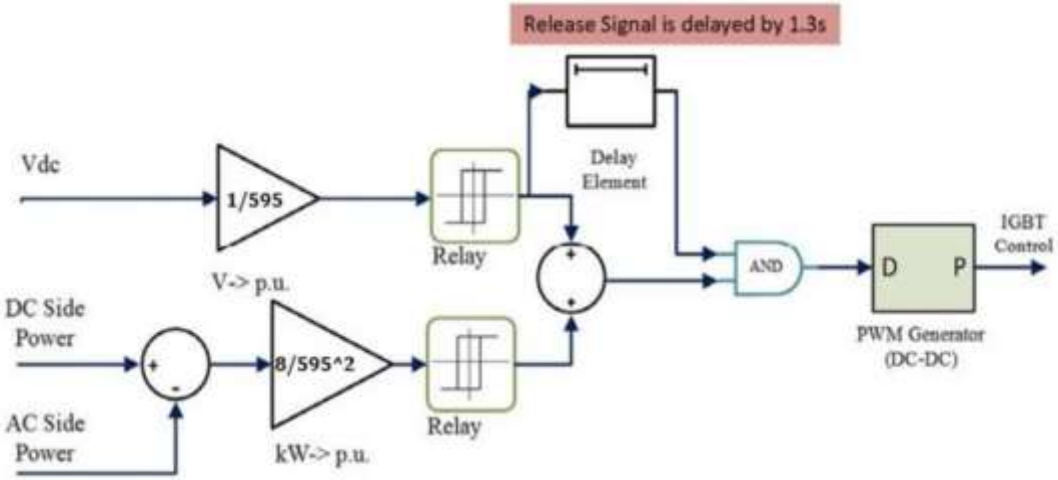


Fig 3.8 DC Braking chopper control circuit [8]

A Braking chopper system that had an 8 ohm chopper resistance was used as the simulation's model. The DC-Link voltage loop relay activates at this point and disengages at 90 percent of the utmost voltage that a typical DC-Link capacitor can resist, which is

120 percent of its rated value. Until the imbalanced power exceeds 25 Watt and the voltage loop relay is currently active, however the power loop relay is still inactive. After the imbalanced power is eliminated, the power loop relay opens. In order to maintain the proper state of affairs after the low voltage disturbances have stopped, Braking Chopper keeps a connection for an further 1.3 S. The IGBT turned on at 0.6 seconds due to an imbalanced state in the DC-Link capacitor, turning on the voltage loop relay. The BC resistance was consequently linked across the DC-Link capacitor to saturate the voltage imbalance. The disruption only lasted for 0.7 second, however the BC remained connected for a further 1.3 seconds to preserve the status quo. When the BC was attached, the 8 ohm resistance's power consumption stayed essentially constant at 50 kW [8].

CHAPTER FOUR

RESULT AND DISCUSSION

- Step 1: Studied the basic theories and literature related to the project.
- Step 2: Developed the MATLAB simulation model of a 50 KW grid connected PV system.
- Step 3 : Developed the MATLAB simulation model of a 50 KW grid connected PV system and observed the fault
- Step 4 : Developed the MATLAB simulation model of a 50 KW grid connected PV system with LVRT control strategy.

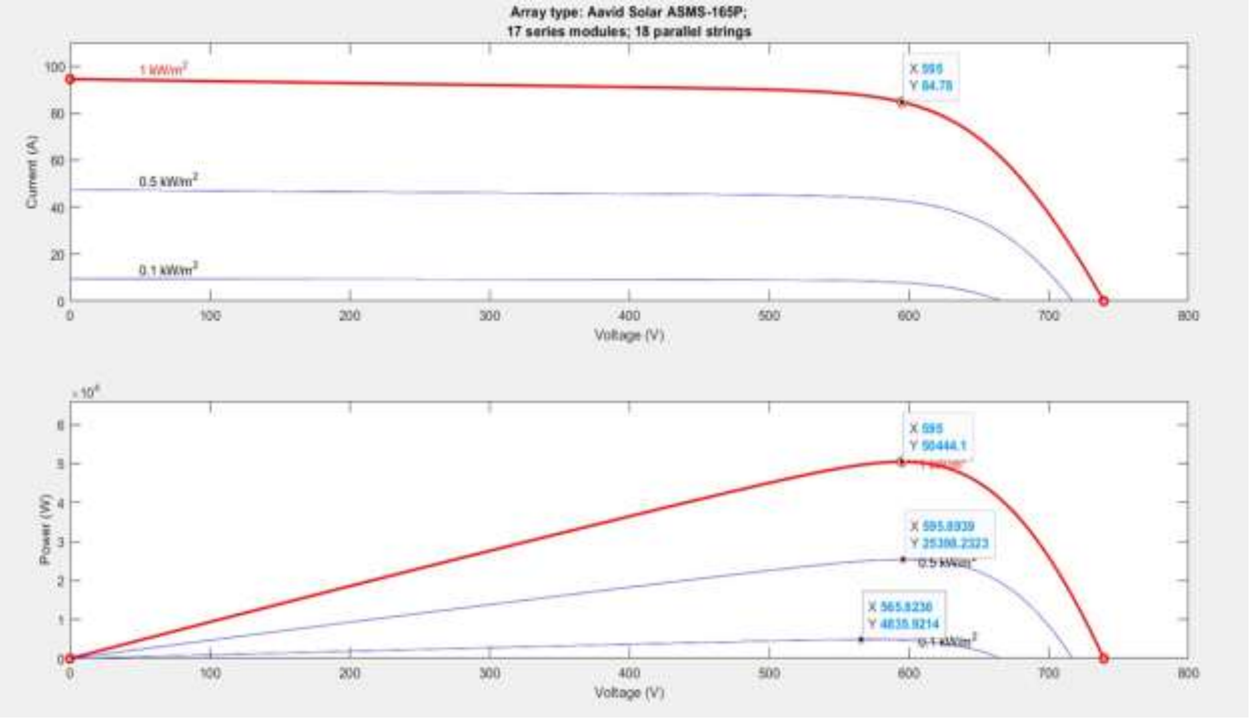


Fig 4.1 I-V and P-V characteristics of PV system at different irradiance level [13]

4.1 PV panel characteristics

A combination of parallel and series strings of PV panel have been placed such that it provides 50.444 KW power .Power supply varies according to the irradiance and temperature. For maximum power delivery to the grid at given irradiation, voltage has to be maintained at the level where maximum power transfer occurs.

Selection of PV panel

Table 4.1: PV specifications

Components used	Aavid Solar ASMS-165 P
Maximum Power	164.85 W
Open Circuit Voltage (V_{OC})	43.5 V
Short Circuit Current (I_{SC})	5.25 A
Parallel strings	18
Series-connected modules per string	17
Total open circuit voltage	17*43.5 = 739.5 V
Total maximum Power	18*17*164.85 = 50444.1 W

From Fig 4.1:

- Maximum power at 1000 irradiance level = 50.444 KW
- Maximum power at 500 irradiance level = 25.398 KW
- Maximum power at 100 irradiance level = 4.835 KW
- Temperature used for the simulation = 25 °C

4.2 Curves obtained during the simulation of 50 KW grid connected PV system

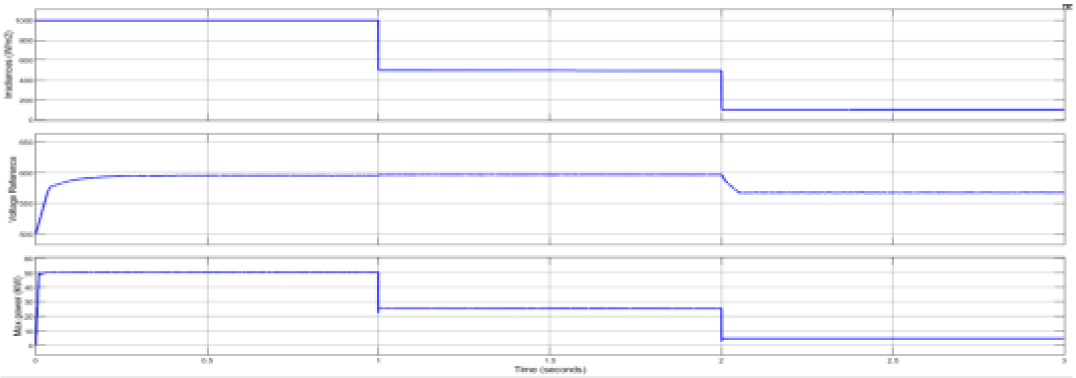


Fig 4.2 Maximum power point tracking demonstration

From the fig 4.2, We can see the tracking of the maximum power at different irradiance level at the reference voltage tracked from the MPPT which generate the maximum power.

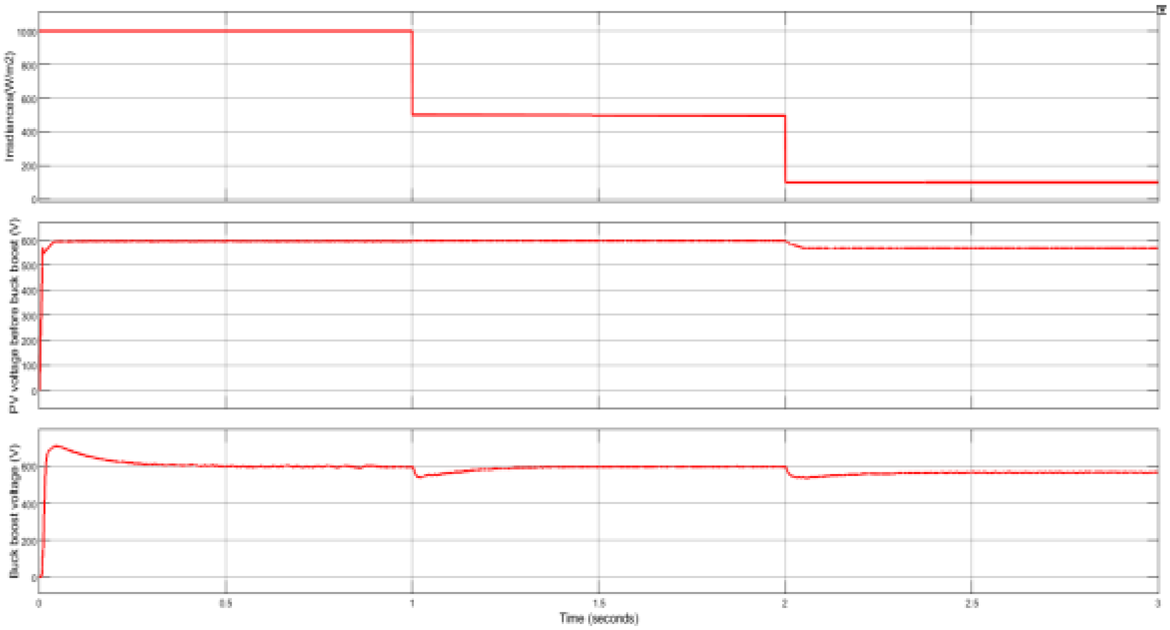


Fig 4.3 PV output voltage and Buck-Boost output voltage for different irradiances

From the Fig 4.3, we can see that the voltage before and after the buck boost are the same i.e PV terminal voltage is equivalent to the voltage after the buck boost converter which is equal to the voltage that corresponds to the maximum power. That means all the maximum power to be generated by the PV system is available to the inverter.

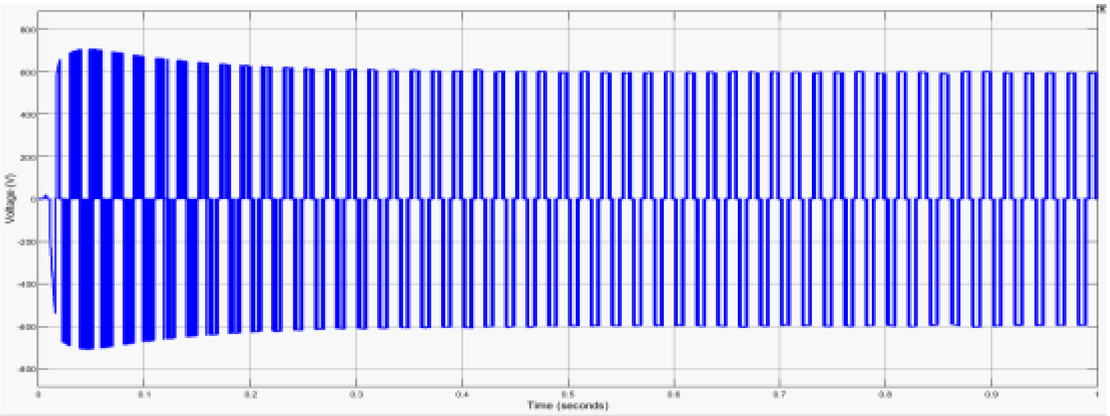


Fig 4.4 Inverter output voltage before filtering

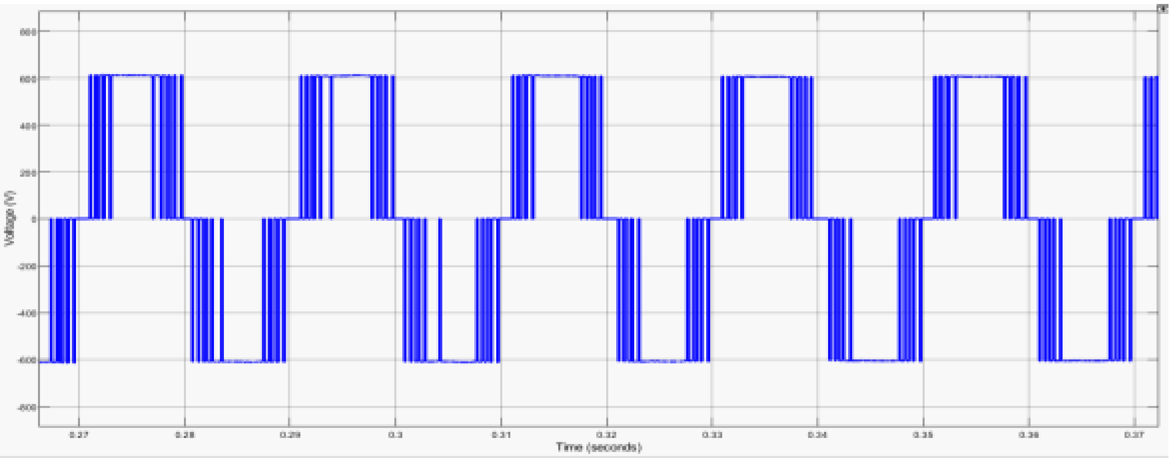
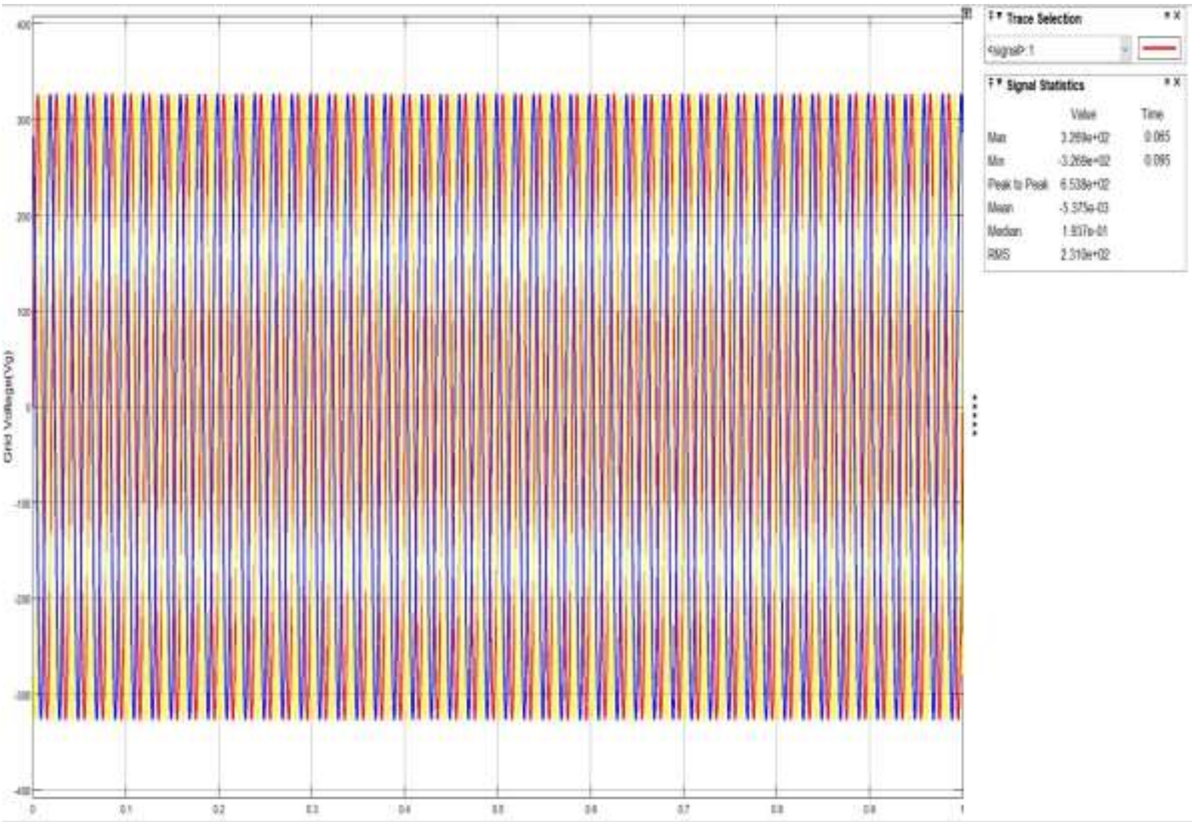


Fig 4.5 Magnified view of inverter output voltage before filtering

Fig 4.5 shows the line waveform at output of inverter and its magnified view. Curve follows the quasi-square type waveform because of switching of IGBT and its peak value is equal to that of input voltage.



	Value	Time
Max	3.269e+02	0.065
Min	-3.268e+02	0.095
Peak to Peak	6.538e+02	
Mean	-5.375e-03	
Median	1.937e-01	
RMS	2.310e+02	

Fig 4.6 Grid side voltage

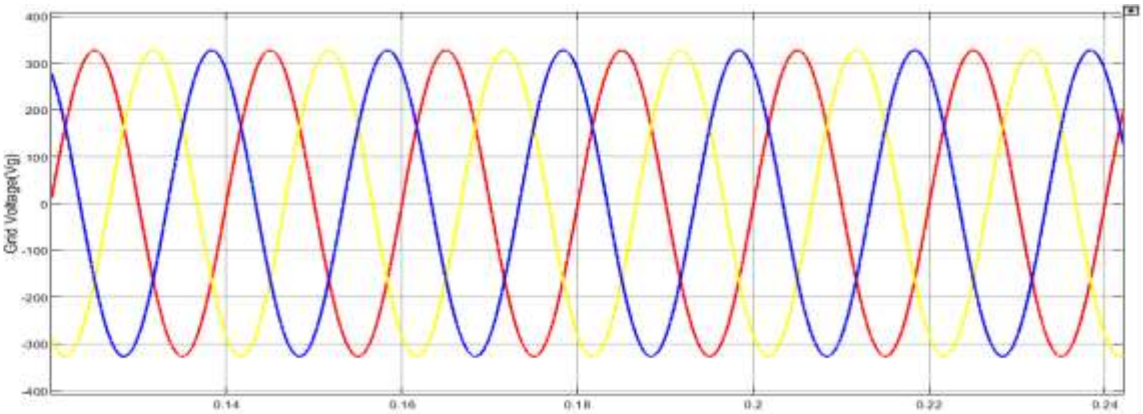


Fig 4.7 Magnified view of grid side voltage

From the fig 4.7 the grid voltage is 400V (Phase to phase) and peak phase voltage is around 326V which is tracked as shown by the graph.

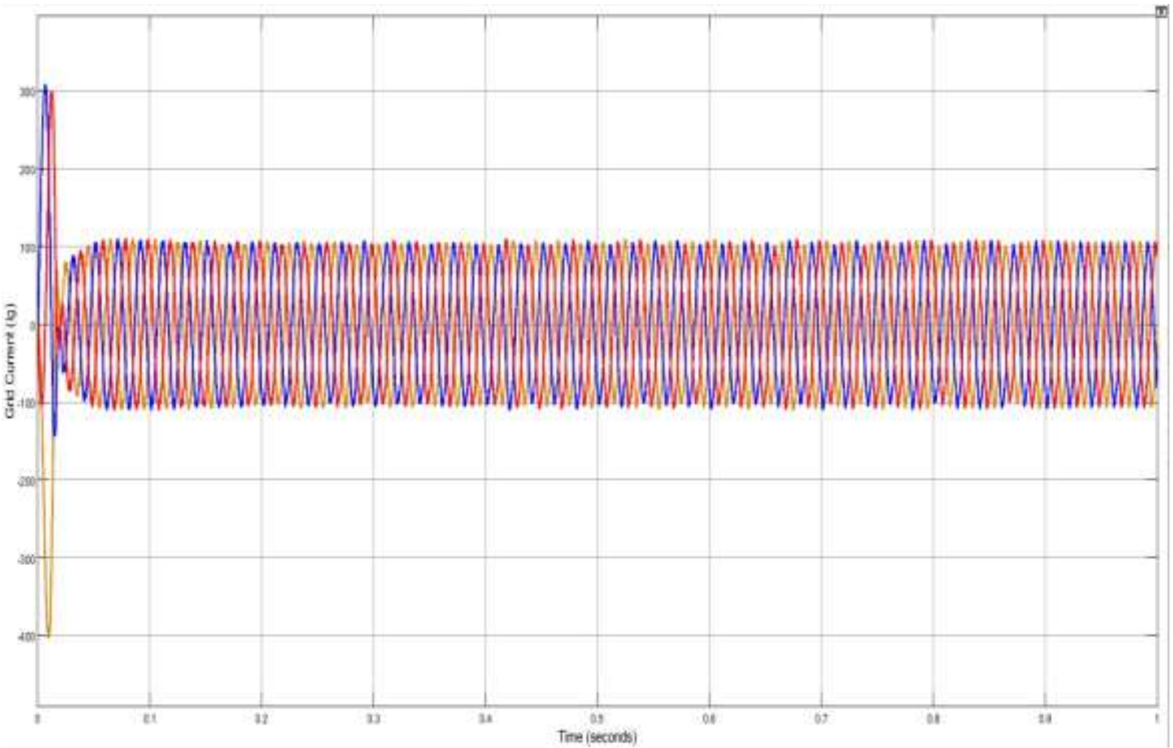


Fig 4.8 Grid side current for irradiance of 1000 W/m^2

Theoretical value of grid side peak current for 1000 W/m^2

I = (50*10^3*√2)/(√3*400) = 102.06 A

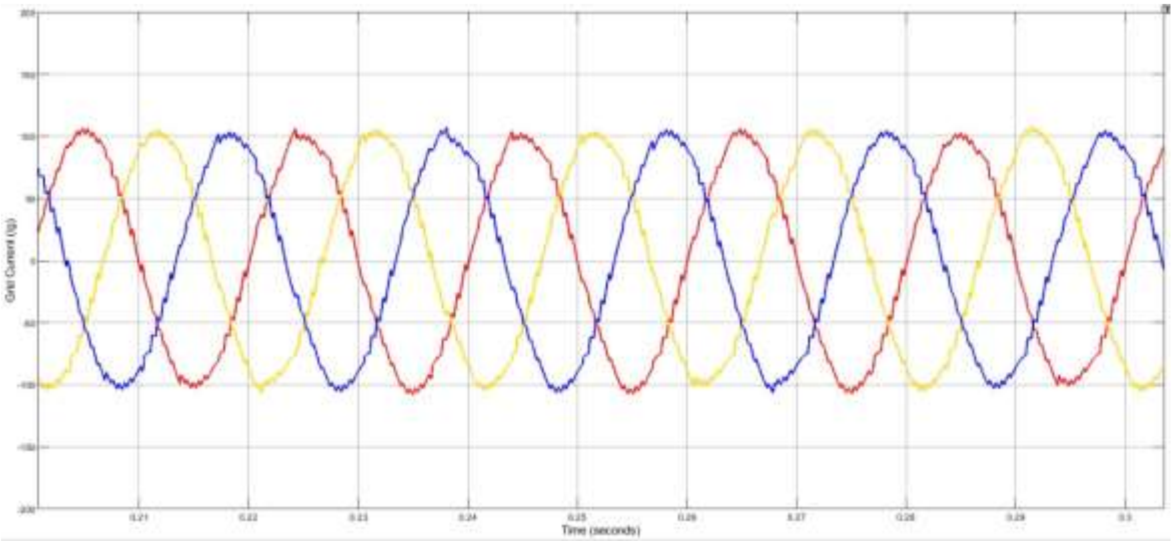


Fig 4.9 Magnified view of grid side current

Maximum peak phase current delivered to the grid is 102A which is equivalent to the actual theoretical value (102.06 A) which should flowing to the grid. Hysteresis band current controller is used to regulate the current delivered to the grid which is not smooth because of band limit used in hysteresis such that switching losses will be minimum and practical switching of IGBT will be achieved.

From the Fig 4.10, we can see that power delivered to the grid for irradiances of 1000 W/m^2 and 500 W/m^2 is nearly 50 KW and 26 KW which is nearly equal to the theoretical maximum power of PV.

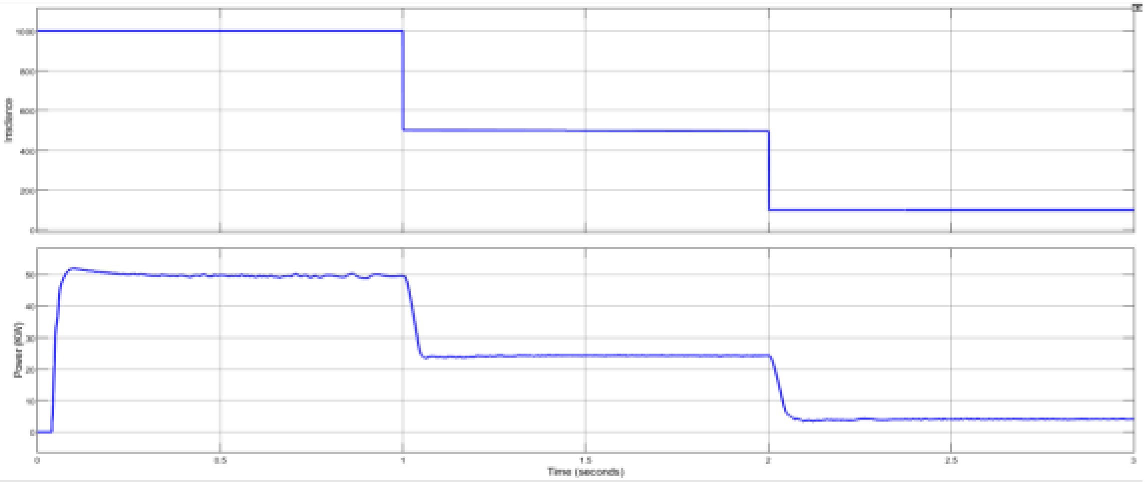


Fig 4.10 Power delivered to grid at irradiances of 1000 W/m2, 500 W/m2 and 100 W/m2

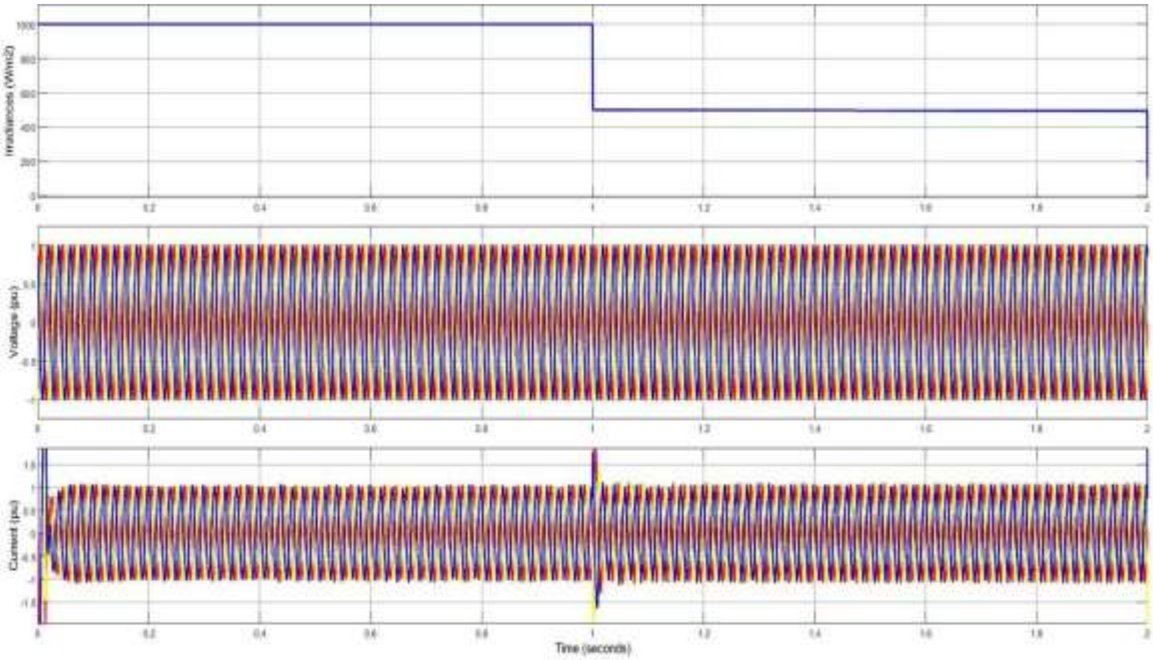


Fig 4.11 Grid side phase voltage and current in p.u. for different irradiance level

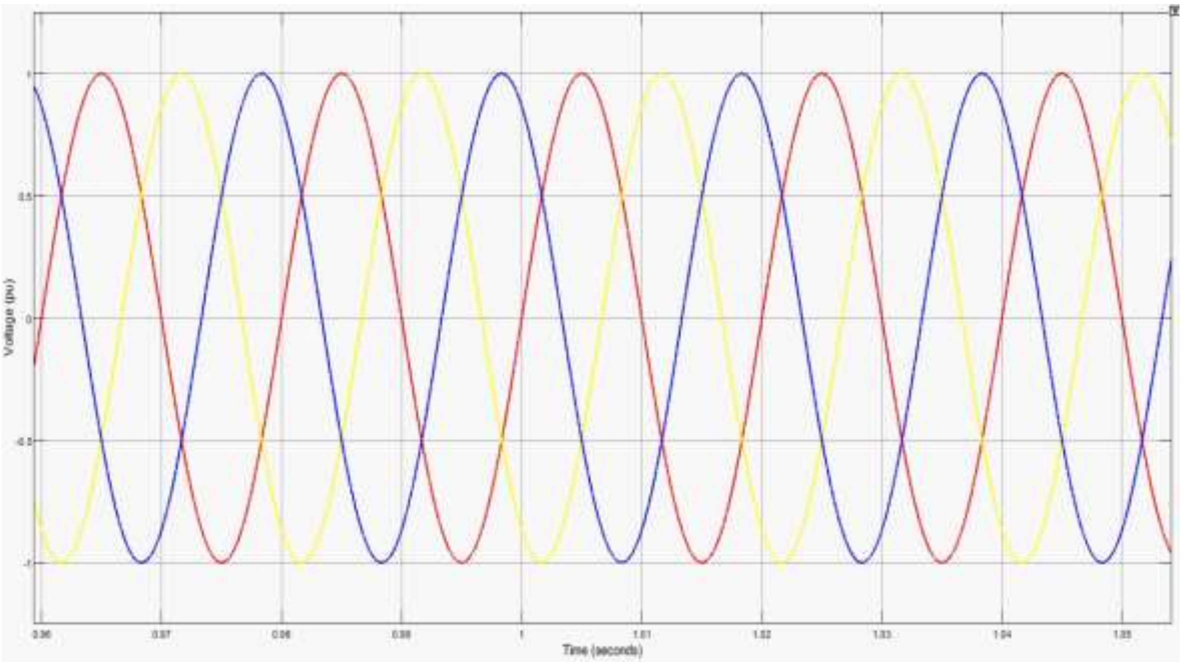


Fig 4.12 Magnified view of grid side phase voltage in p.u.

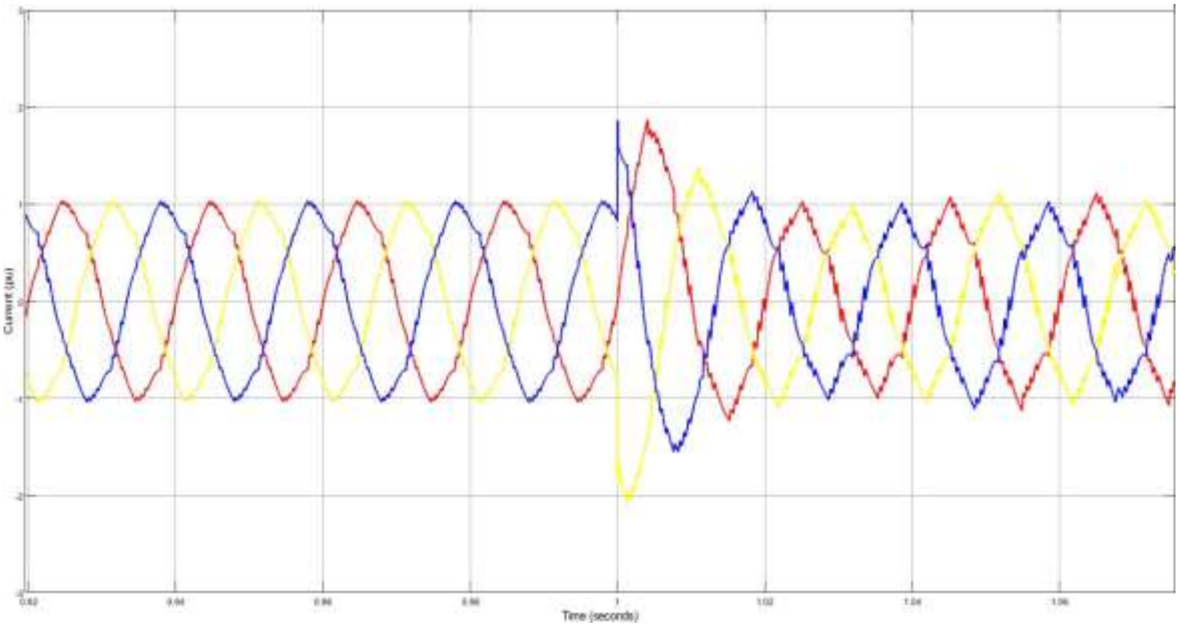


Fig 4.13 Magnified view of grid side phase current in p.u.

From the figure 4.13, we can say that peak voltages and current delivered to load are always 1 PU for all irradiance. The ripple is seen due to higher hysteresis bands. We used +- 5% of Iref as a hysteresis band so that there will be low switching loss.

4.3 Simulation results during single phase to ground fault without DC Braking Chopper

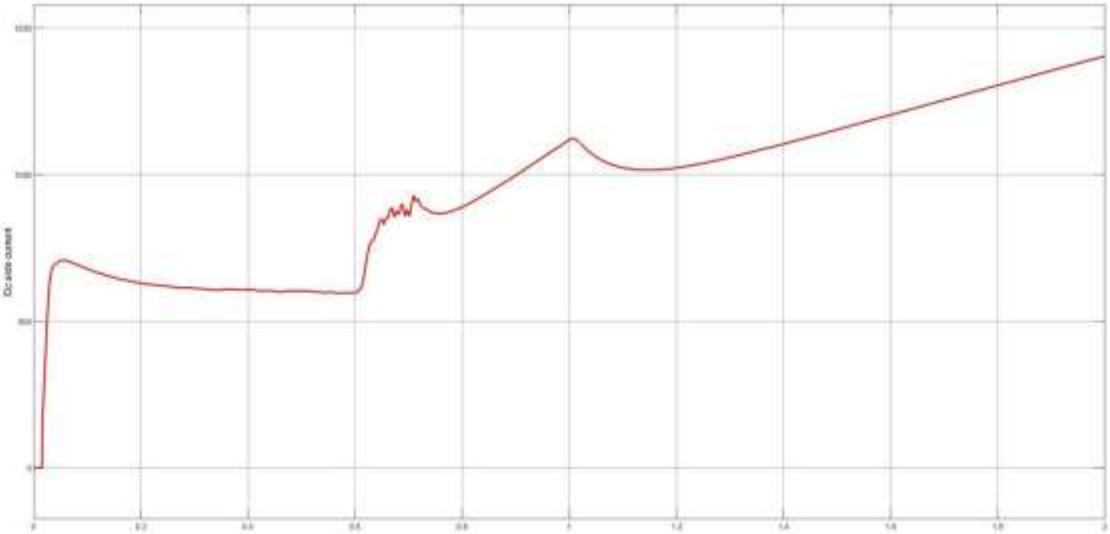


Fig 4.14 DC voltage without DC Braking Chopper during fault

- DC voltage curve

After a transient fault occurs at 0.6 sec, total power generated by the PV system is not transferred to the grid and excess power is used to charge the DC link capacitor due to which DC link voltage rises continuously and ultimately damages the capacitor without proper control strategy. The maximum value of DC link voltage is 925 V at 0.7 sec.

- DC current curve

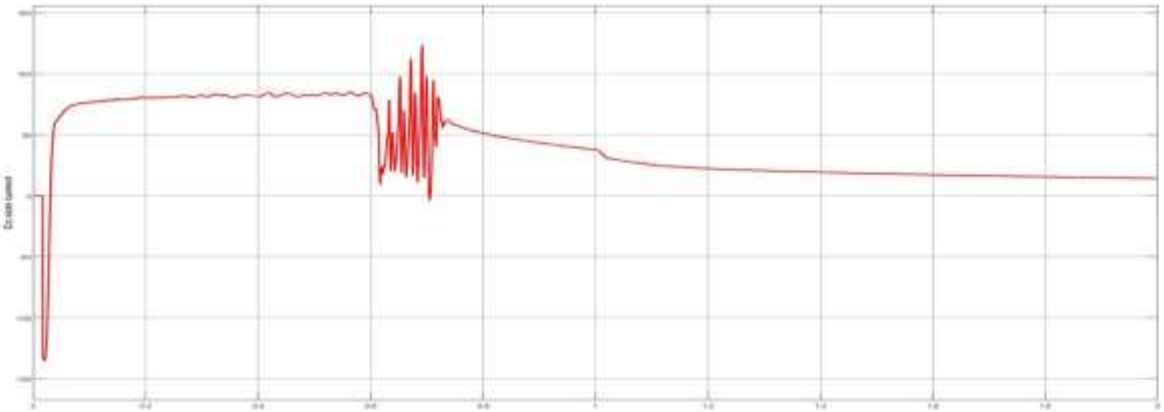


Fig 4.15 DC current without DC Braking Chopper during fault

For the same power generated by a PV system, since DC voltage rises continuously in faulty condition, the DC current decreases accordingly. The maximum value of DC current delivered by the PV system is equal to 122 A at 0.693 Sec.

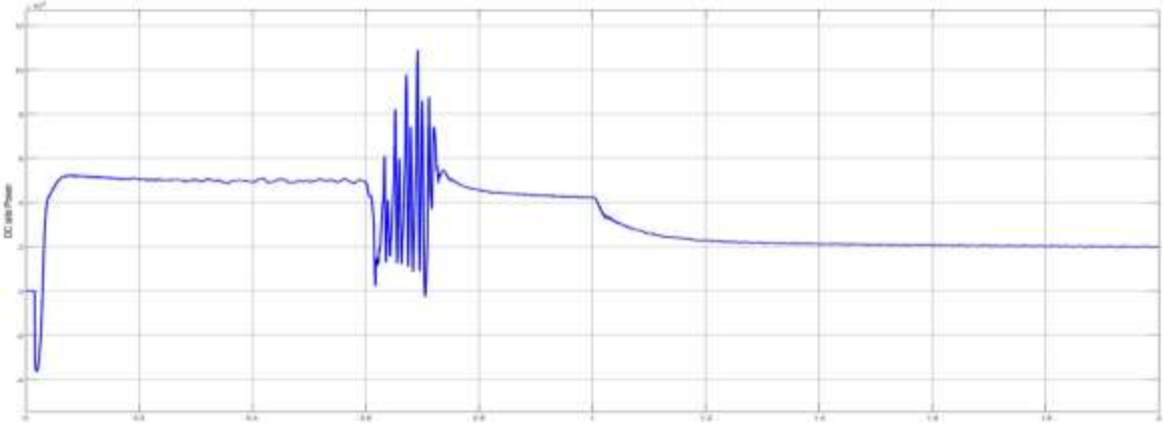


Fig 4.16 DC side power without DC Braking Chopper during fault

- DC power curve

Fig 4.16 shows the DC power curve which is equivalent to the power generated by a PV system.

- Grid voltage

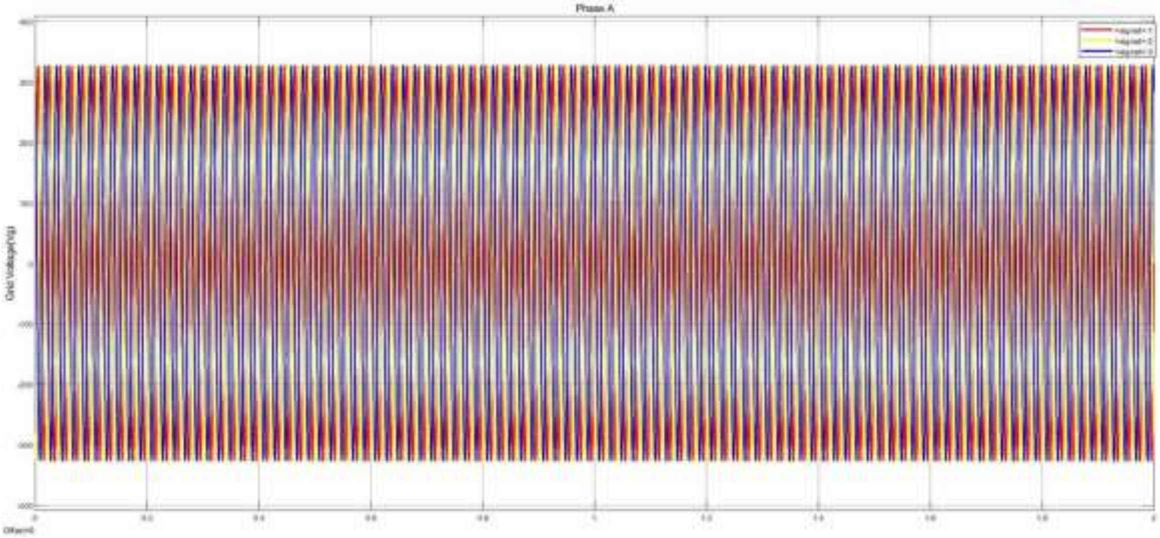


Fig 4.17 Grid side voltage without DC Braking Chopper during fault

There is no fluctuation in grid voltage in faulty condition due to compensation of voltage by interconnected power systems. Bus system used in MATLAB was slack bus due to which voltage remains the same.

- Grid power at different irradiance level

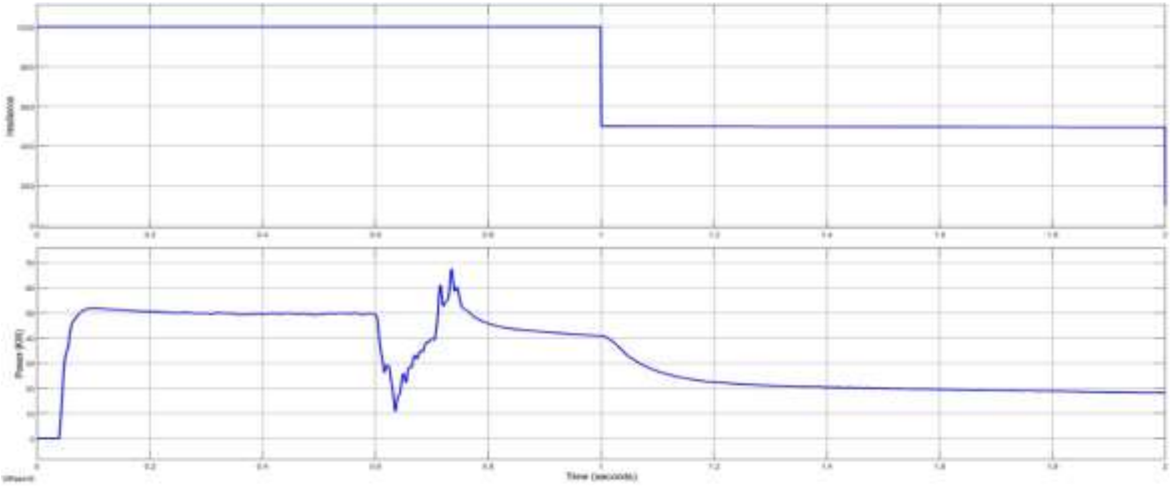


Fig 4.18 Grid side Power without DC Braking Chopper at different irradiance level

From fig 4.18, we can see that the power accepting capacity of the grid is decreasing continuously after transient fault occurs.

- Grid side power at constant 1000 irradiance

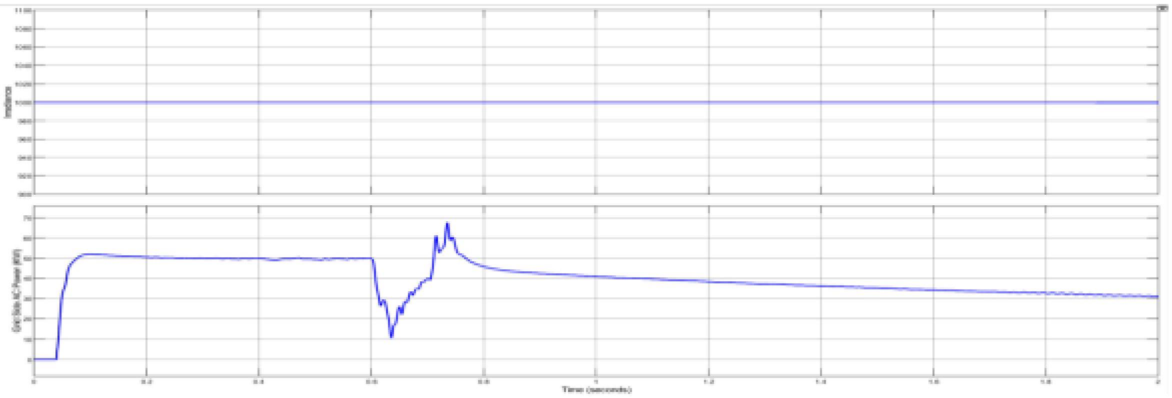


Fig 4.19 Grid side Power without DC Braking Chopper at constant 1000 irradiance

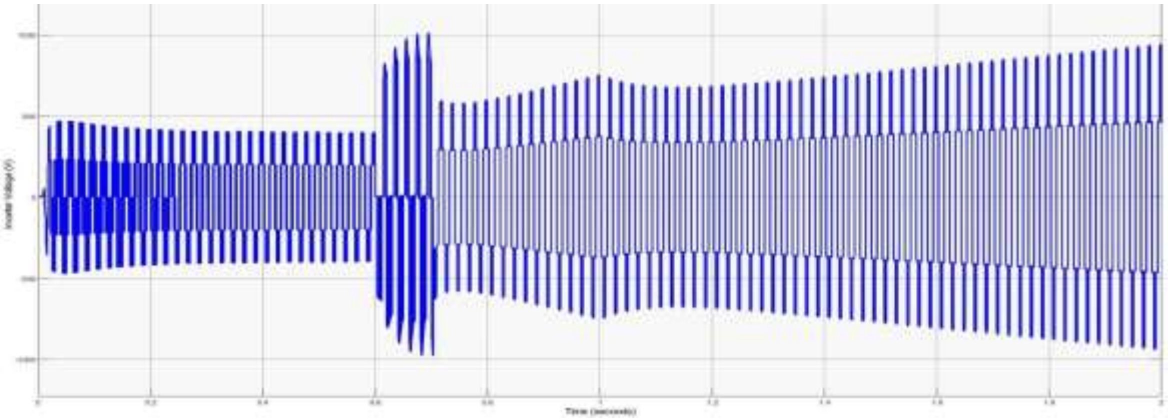


Fig 4.20 Inverter voltage without DC Braking Chopper during fault

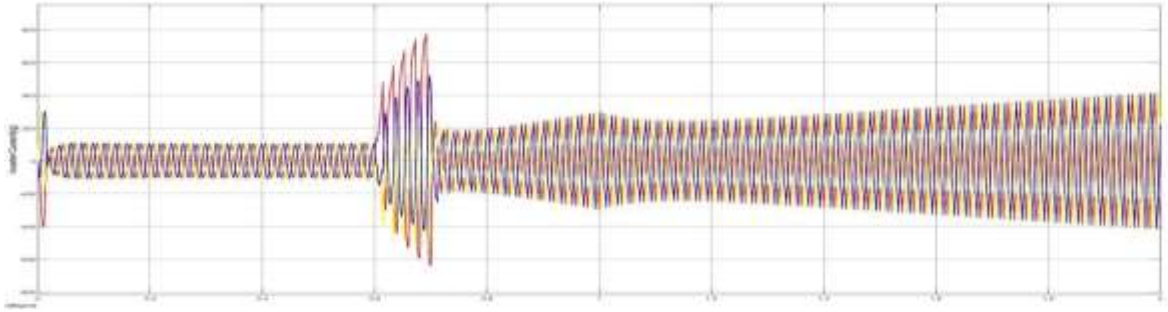


Fig 4.21 Inverter current without DC Braking Chopper during fault

- Inverter voltage curve

From fig 4.20, Peak value of inverter phase voltage is equal to 1000 V at 0.69 sec.

- Inverter current curve

From fig 4.21 it is seen that, inverter voltage and inverter current increases to higher value during the fault condition which may damage the inverter. The majority of inverter current is delivered by the grid. The maximum value of peak phase current is equal to 774.9 A at 0.693 Sec.

4.4 Simulation results during single phase to ground fault with DC Braking Chopper

- DC voltage curve

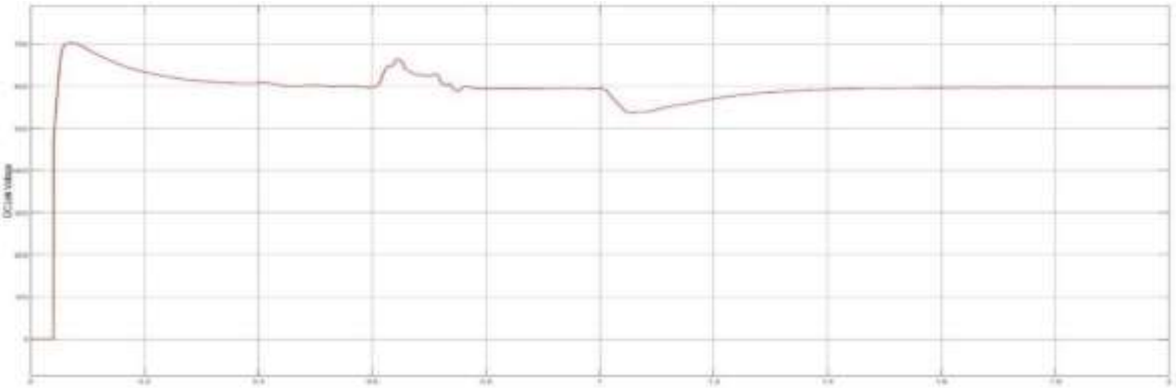


Fig 4.22 DC Voltage during single phase to ground fault with DC Braking Chopper

Since DC link voltage was continuously rising due to occurrence of fault which may damage the capacitor. But after using the DC braking chopper, this voltage fluctuates during fault condition and remains stable to the reference voltage. Since, almost greater than 90% of the reference voltage is able to be tracked within 1.5 seconds; we are able to achieve the fault ride through requirement according to the German grid code standard. From fig 4.22, maximum voltage across DC link capacitor is found to be 665 V at 0.644 sec.

- DC current curve

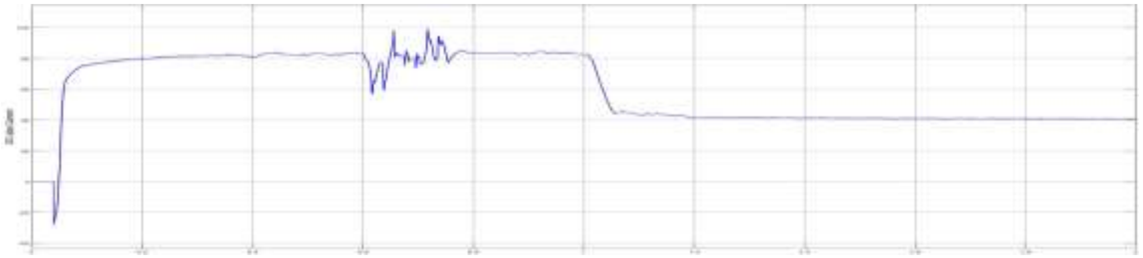


Fig 4.23 DC current during single phase to ground fault with DC Braking Chopper

DC side current rises to the high value during fault condition but after working of DC chopper, it is able to settle down to its normal value. From fig 4.23, Maximum Dc current during fault is found to be 98 A at 0.718 sec.

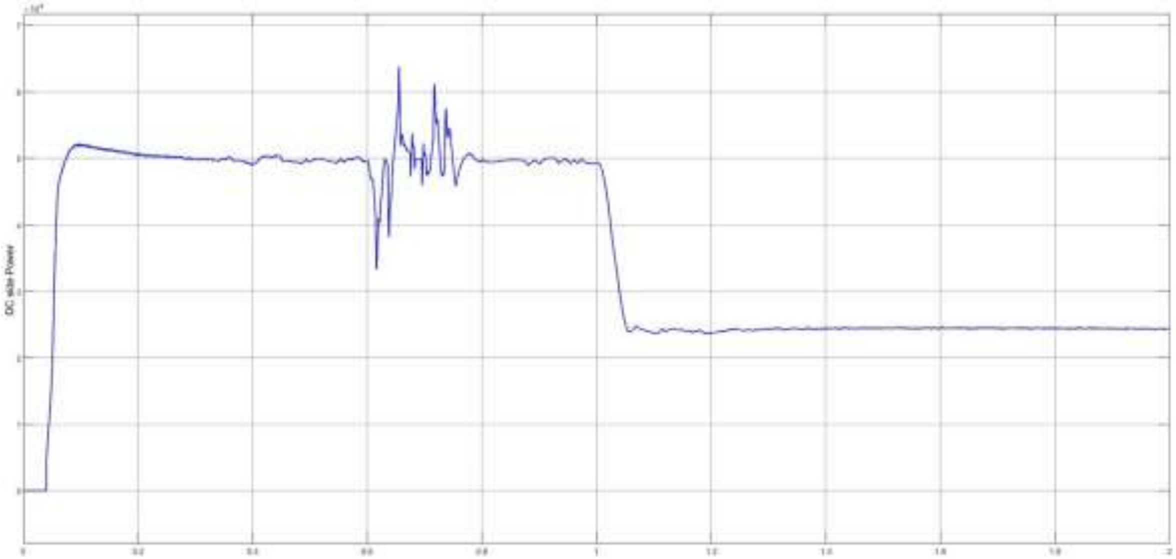


Fig 4.24 DC power during single phase to ground fault with DC Braking Chopper

- DC power curve

DC power is the power generated by a PV system which is in accordance with the Power-Voltage curve.

- Inverter voltage curve

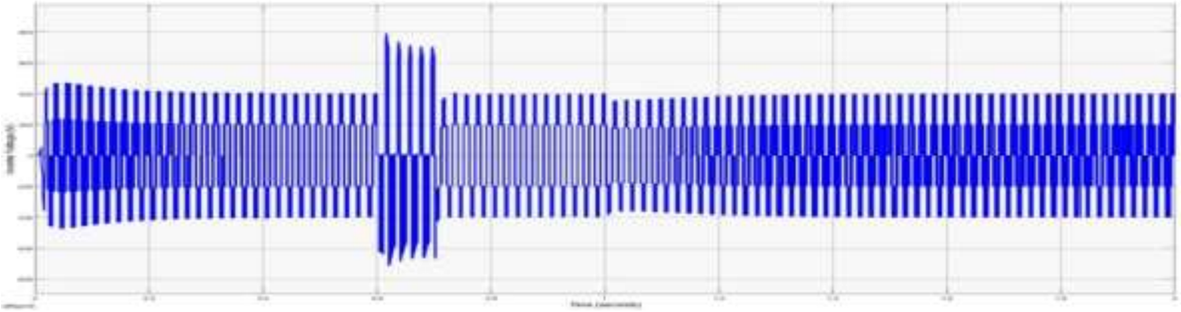


Fig 4.25 Inverter Voltage during single phase to ground fault with DC Braking Chopper

Inverter voltage will also settle down to its normal value providing that inverter may not experience the overvoltage and doesn’t disconnect from the grid. This fulfills the fault ride through requirement. From figure, Peak value of inverter phase voltage is found to be 794.5 V at 0.616 sec.

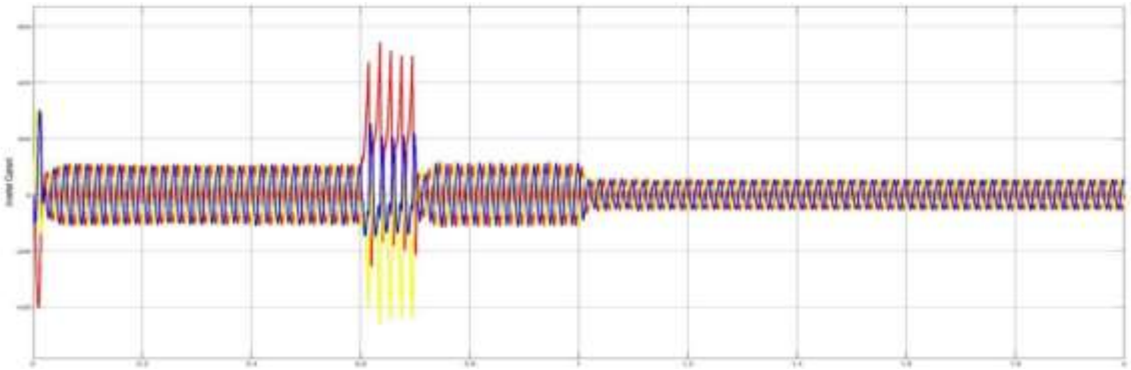


Fig 4.26 Inverter current during single phase to ground fault with DC Braking Chopper

- Inverter current curve

From the fig 4.31, during fault conditions, inverter current rises because some part of fault current is supplied by the inverter and after the elimination of fault, the current through the inverter falls down to its normal value. The peak value of inverter phase current is found to be 544 A at 0.636 Sec.

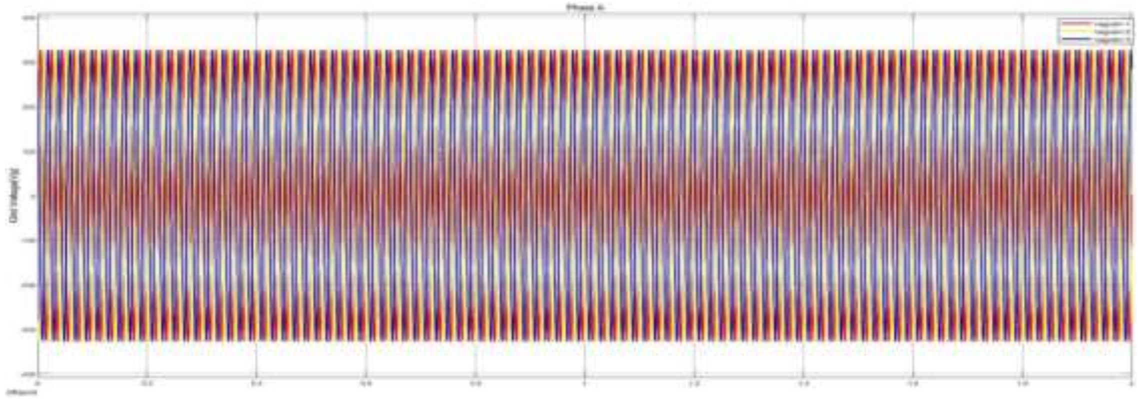


Fig 4.27 Grid side voltage during single phase to ground fault with DC Braking Chopper

- Grid side voltage curve

Grid voltage is not affected by the fault conditions. It is because the bus used was a swing bus in the MATLAB whose bus voltage always remains at unit PU value. The peak value of grid phase voltage is equal to 326 V.

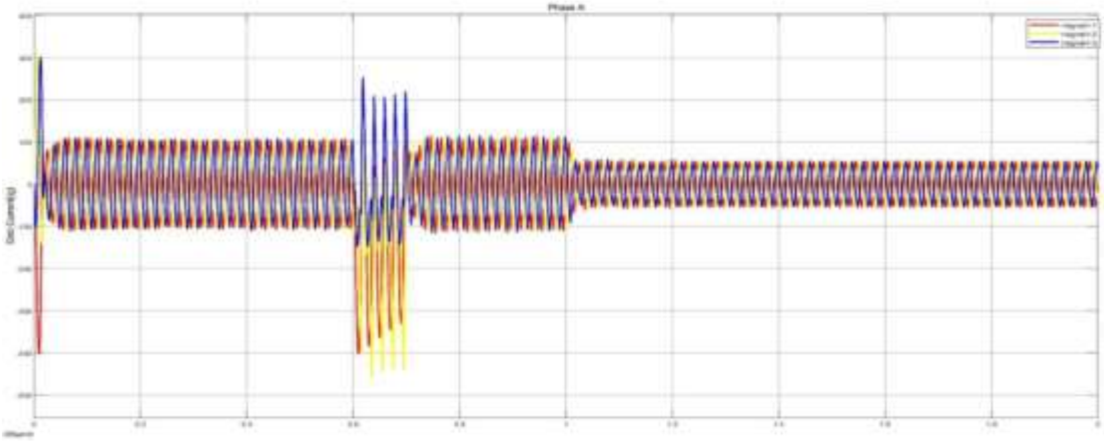


Fig 4.28 Grid side current during single phase to ground fault with DC Braking Chopper

- Grid side current curve

During the fault conditions, the Grid current also rises because some part of fault current is supplied by Grid and after elimination of fault, grid current falls down to its original value.

- Grid side power curve

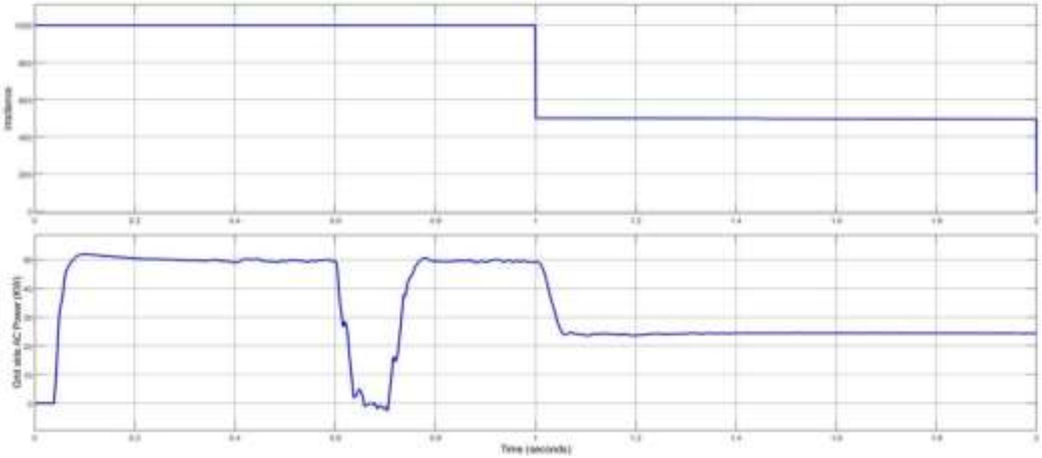


Fig 4.29 Grid side power during single phase to ground fault with DC Braking Chopper

The injected power to the grid during fault condition is almost equal to zero because total power supplied by PV system is dumped to DC braking chopper using 8ohm resistance. After the elimination of fault, total respective power generated by PV system is supplied to the grid at corresponding irradiance levels. 50 KW of power is injected to grid at 1000 irradiation,25 KW power is injected to grid at 500 irradiation and so on.

4.5 Summary of results

Table 4.2 Value of DC voltage and current and Inverter voltage and current

For LG fault on inverter side	DC link voltage	DC current	Inverter voltage (Peak Phase)	Inverter Current (Peak Phase)
Without DC Braking Chopper	925 V at 0.7 Sec	122 A at 0.693 Sec	1000 V at 0.69 Sec	774.9 A at 0.693 Sec
With DC Braking Chopper	665 V at 0.644 Sec	98 A at 0.718 Sec	794.5 V at 0.616 Sec	544 A at 0.636 Sec

4.6 Discussion

From the above table, it is seen that by using DC Braking chopper, maximum DC voltage across the DC link capacitor during the fault is reduced by 260 V and the maximum value of current delivered by the PV system is reduced by 24 A. Likewise, the peak value of inverter phase voltage is reduced by 206 V and peak value of inverter phase current is reduced by 230 A during the fault. Thus by the use of DC braking chopper, the voltage and current of the DC link capacitor and inverter are reduced to the safer value which ensures the protection of DC link capacitor from overvoltage and inverter from overcurrent and PV system does not disconnect from grid which fulfills the requirement of fault ride through capacity of grid tied inverter.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

For the two-stage grid-integrated solar PV system to improve low voltage ride through (LVRT), a DC Braking Chopper technique has been developed in this research. A 50 KW grid-connected PV system simulation model has been created. The maximum power from PV systems at varying irradiances is extracted using the maximum power point tracking (MPPT) technique. By keeping the DC link voltage at a level that is equal to the voltage that corresponds to the maximum power, the inverter may be controlled to produce the correct switching pattern needed for IGBTs to extract the maximum amount of power. On the inverter side, a single phase to ground (LG) fault is visible, which causes the DC link capacitor voltage to overshoot and the inverter to overcurrent. The proposed DC Braking control approach consists of a resistor that absorbs the extra energy in the DC link capacitor during the fault, which will regulate the DC-link overvoltage and limit the overcurrent through the inverter, where the necessary PWM signal for the IGBT used in the DC braking chopper is generated by the principle of power balance between the DC side and AC side. The maximum voltage across the DC link capacitor decreases from 925 V to 665 V after the operation of the DC brake chopper, and the maximum current flowing through the inverter decreases from 774.9 A to 544 A. As a result, the PV system won't disconnect from the grid because the capacitor voltage and inverter current won't exceed their safe limits. After the problem has been eliminated, the system becomes stable, even for a transient fault lasting 0.2 seconds. These outcomes satisfy the grid-connected inverter's fault ride through (FRT) criteria.

5.2 Recommendation

- Study the effect of different DC link capacitor sizes: The effectiveness of DC Braking chopper is highly dependent on the size of DC link capacitor. Future research can focus on studying the effect of different sizes of capacitor on the overall system reliability and performance.

- Study the impact of DC braking chopper on system efficiency: The use of DC braking chopper adds additional losses to inverter system. Future research can focus on studying the impact of DC braking choppers on system efficiency and developing techniques to minimize losses.
- Study the impact of DC braking chopper on device reliability: DC braking chopper can cause voltage spikes, which can lead to the device failures and reduces the reliability of the inverter system. Future research can focus on the studying the impact of DC braking choppers on device reliability and developing the techniques to mitigate these losses.
- Evaluate the compatibility of DC braking chopper with different inverter topologies: DC braking chopper may not be compatible to certain types of grid connected inverters. Future research can focus on evaluating the compatibility of DC braking chopper with different grid connected inverter topologies and developing the techniques to overcome any compatibility issues [13].

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APPENDIX

APPENDIX A: MATLAB function code for MPPT

The coding for MPPT is written as:

```
function Vref = refgen(V,I)
Vrefmax = 600;
Vrefmin = 0;
Vrefinit = 500;
deltaVref = 0.01
persistent Vold Vrefold Pold;

if isempty (Vold)
    Vold = 0;
    Pold = 0;
    Vrefold = Vrefinit;
end

P = V*I;
dV = V - Vold;
dP = P - Pold;

if dP ~= 0
    if dP < 0
        if dV < 0
            Vref = Vrefold + deltaVref;
        else
            Vref = Vrefold - deltaVref;
        end
    else
        if dV < 0
            Vref = Vrefold - deltaVref;
```

```
        else
            Vref = Vrefold + deltaVref;
        end
    end
else
    Vref = Vrefold;
end
if Vref >= Vrefmax || Vref < Vrefmin
    Vref = Vrefold;
end

Vrefold = Vref;
Vold = V;
Pold = P;
end
```

FRT

ORIGINALITY REPORT

20%
SIMILARITY INDEX

PRIMARY SOURCES

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