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Control of Grid-Tied Inverter During Unbalanced Transient Fault

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Abstract— **With increasing use of renewable and clean form of energy, PV systems have become popular due to its versatility and easy implementation. The overall performance of grid-connected PV systems is directly influenced by the performance of grid-tied inverter. Hence, control of grid-tied PV inverter has become a temptation. This project explores the development of grid-connected PV system and optimization of control strategies for grid-tied inverter to ensure its seamless operation and grid stability during transient faults. The transient faults occurring at the inverter side disrupts the normal operation of inverter and even lead to shut down of inverter during faults.**

Therefore, a control strategy is suggested and developed to control the overvoltage of DC-link capacitor and deliberately functioning and output of grid-tied inverter is improved. This is simply possible by introducing ELC so that the inverter needs not be shut down.

Keywords—***Grid-tied inverter, Transient fault, PV system ELC, Boost converter, Overvoltage, Three-phase inverter Unbalanced Fault.***

Introduction

A photovoltaic system (PV) system is a system composed of one or more solar panels combined with inverter, other electrical components and mechanical components that use solar energy to generate electricity. It is connected to grid through an inverter. Whenever a symmetrical or unsymmetrical transient fault appears on the grid side, the grid provides most of the fault currents so the inverter operation on the PV side is not disturbed.

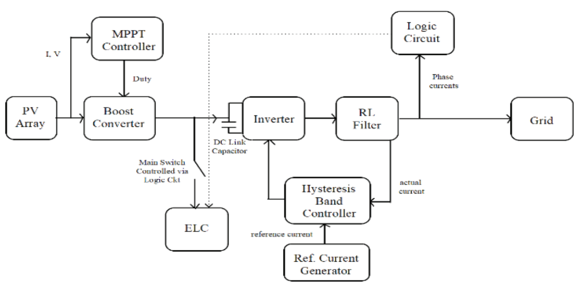

Fig 1 Block diagram of grid connected PV system

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Photo Voltaic Array

A photovoltaic (PV) array, also known as a solar array, is a system of interconnected solar panels or modules that convert sunlight into electrical energy. It is a key component of a solar power system.

The PV array consists of multiple solar panels, typically made of semiconductor materials such as silicon, which can generate electricity when exposed to sunlight. Each solar panel contains a collection of photovoltaic cells, also known as solar cells, which are responsible for the conversion of sunlight into electricity through the photovoltaic effect.

When sunlight hits the surface of the solar panels, photons (particles of light) transfer their energy to the electrons in the semiconductor material of the solar cells as shown in Fig 2. This energy excites the electrons, allowing them to flow as an electric current. The electrical current is then captured by the wiring within the PV array and can be used to power electrical devices, transmit the energy to the grid directly or stored in batteries for later use.

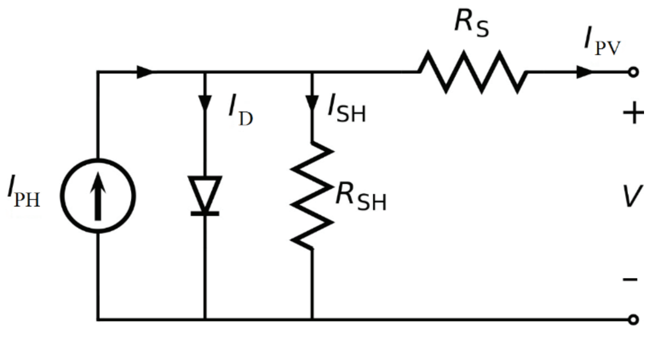

Fig 2 Model of a PV cell

The size and capacity of a photovoltaic array can vary depending on the desired electrical output. In large-scale solar installations, such as solar power plants, hundreds (even thousands) of solar panels are connected together in an array to generate significant amounts of electricity. Fig 3 shows the model of a PV array. In order to increase the voltage output of the PV Systems, more solar panels are connected in series while to increase the power output of the system, more solar panels are connected in parallel.

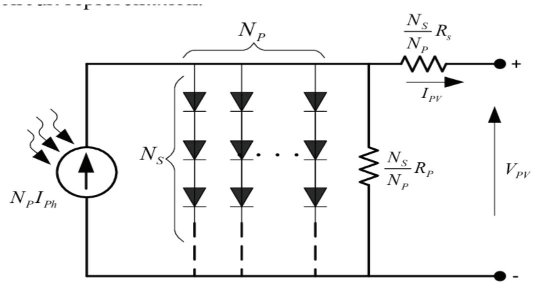

Fig 3: Model of a PV array

Maximum Power Point Tracking (MPPT)

MPPT stands for Maximum Power Point Tracking, and it refers to a system used in solar power plants and solar charge controllers to maximize the efficiency and power output of photovoltaic arrays. The output power of a photovoltaic (PV) module or array is dependent on various factors, such as temperature, shading, and the intensity of sunlight. The maximum power point (MPPT) is the operating point at which the PV module or array generates the maximum power output for a given set of conditions.

An MPPT system is designed to continuously track and adjust the operating point of the PV array to maintain it at the MPP. This is achieved by employing advanced electronics and algorithms that monitor the voltage and current characteristics of the PV array and determine the optimal operating voltage and current levels for maximum power output. The primary function of an MPPT system is to ensure that the PV array operates at its MPP, even when environmental conditions change, such as when clouds pass over or the temperature fluctuates. By dynamically adjusting the operating point, the MPPT system maximizes the power harvested from the PV array and improves the overall efficiency of the solar power plant. MPPT systems are particularly useful in grid-connected solar power plants, where the generated electricity is fed into the utility grid. They are also commonly used in off-grid solar systems, where the harvested energy is stored in batteries for later use, ensuring efficient charging and utilization of the battery bank.

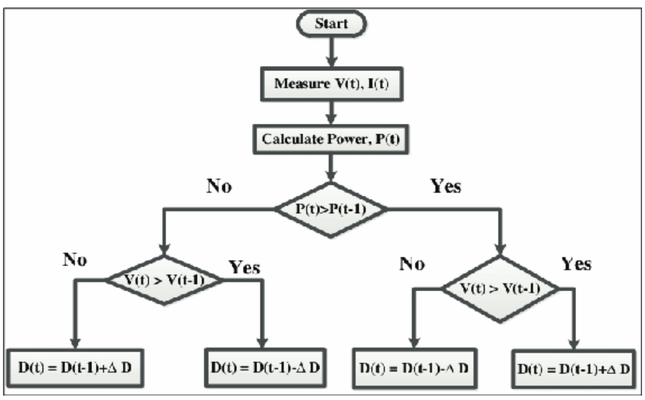

Fig 4 Flowchart of P&O MPPT Logic

In P&O MPPT logic, the operating voltage of the solar panel is perturbed or adjusted in small increments, and the resulting power output is observed. Fig 4 shows the flowchart of P&O MPPT logic and its algorithm works as follows:

a) Perturbation: Initially, the solar panel operates at a predefined voltage or power point. The algorithm perturbs the operating voltage by a small amount, typically incrementing or decrementing it, to explore the power-voltage curve of the solar panel.

b) Observation: After the perturbation, the power output of the solar panel is observed and compared with the previous power output. If the power output increases, the perturbation is continued in the same direction. However, if the power output decreases, the perturbation is reversed, and the voltage is adjusted in the opposite direction.

c) Tracking: The process of perturbation and observation is repeated iteratively to track the MPP. The algorithm dynamically adjusts the operating voltage of the solar panel, always moving in the direction that increases the power output until the MPP is reached.

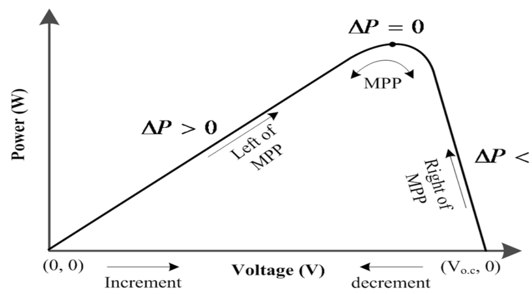

Fig 5 Perturbation and Observation (P&O)

P&O MPPT logic is based on the assumption that the MPP lies between the previous and current operating points and this is depicted by fig 5. However, it has some limitations, such as the potential for oscillations around the MPP under rapidly changing irradiance conditions.

Despite these limitations, P&O MPPT logic remains popular due to its simplicity, low computational requirements, and effectiveness under certain operating conditions. It has been widely implemented in various solar power systems, especially in smaller-scale applications.

Boost Converter

A DC-to-DC boost converter, also known as a step-up converter, is an electronic circuit that increases the input voltage level to a higher output voltage level.

Boost converters are generally used in various applications, such as battery charging systems, renewable energy systems, and LED drivers, where higher voltage is required.

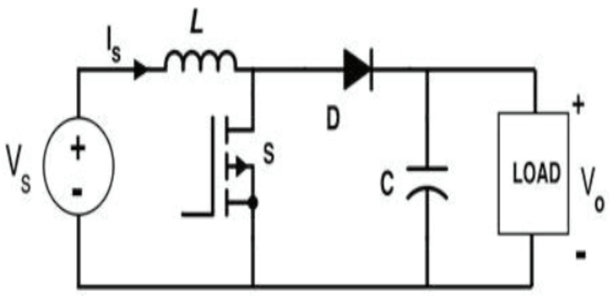

Fig 6 Boost Converter

Fig 6 shows the boost converter which comprises of two active semiconductor components (A diode and a MOSFET) and energy storage elements (An inductor and a capacitor). Boost converters provide efficient voltage conversion and can step up the voltage from sources with lower voltages, enabling the utilization of energy sources that would otherwise be incompatible with the load requirements.

In this scheme, PV output voltage of around 360V has been boosted to 600V dc which is then fed to the dc side of the inverter for conversion.

Output equation: $V_o = V_{in} / (1-D)$

where,

V_{in} = Input Voltage

D = Duty = T_{on}/T_{total}

Three Phase Inverter

A three phase three-level inverter has been used in this scheme. DC input of approx. 600V has been inverted to an AC three phase output of 230V per phase

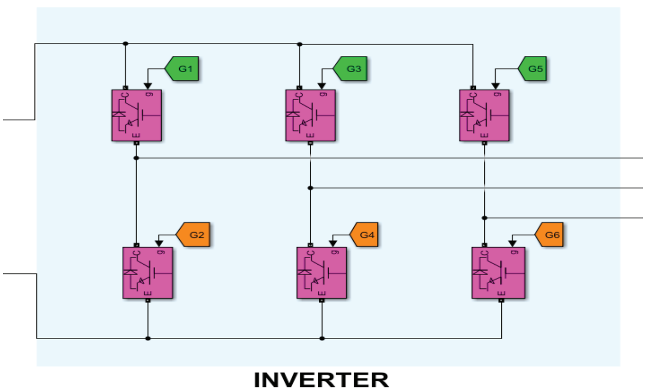

Fig 7 Three Phase Inverter

Six IGBT switches are used in the inverter as shown in Fig 7 These IGBT are controlled using Hysteresis Band Current Control Technique which ensures that the inverter follows the reference current waveform. The controller generates the reference current by sensing the ac terminal voltage and dc voltage across the capacitor in the dc side of the inverter. The hysteresis band current controller compares the actual currents with the reference currents and generates the gate signals to turn on and off the switch pairs T1-T2, T3-T4 and T5-T6 several times in a cycle so that the actual inverter current i0 (actual) tracks the reference current iabc(ref) within a limited hysteresis band.

A RL Filter has been provided at the output of the inverter. The filter smoothens the three-level output of the inverter before implementing the current waveforms with the hysteresis band current control.

Fault Ride through Capacity

The term "fault ride-through capacity" in the context of a PV system refers to the system's ability to withstand and continue to operate during grid disturbances or faults without disconnecting from the grid. Faults can be caused by various events, such as short circuits or sudden changes in load, and they can result in voltage fluctuations or interruptions in the electricity grid. For a PV system connected to the grid, it is essential to have a certain level of fault ride-through capacity to ensure grid stability and reliability. If a PV system were to immediately disconnect from the grid during a fault, it could exacerbate the instability and even cause cascading failures in the grid.

The fault ride-through capability is typically regulated by grid codes and standards, which set the requirements for how power generation systems, including PV systems, should behave during grid disturbances. These standards may specify the allowable voltage and frequency ranges and the time duration for which the system must remain connected and continue to supply power during a fault.

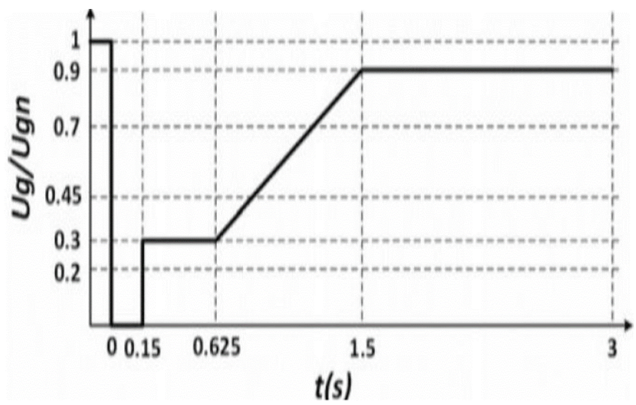

Fig 8 FRT Curve (German EON grid code)

Fig 8 shows the FRT curve. As per the EON (a European multinational electricity utility), if the voltage profile of a grid connected PV system does not return back to 0.9 pu within 1.5sec after fluctuations, then the PV system no longer stays in synchronism with the grid.

So, the grid code demands for the voltage profile to be back within the value greater than 0.9 pu after 1.5 seconds of fluctuations.

ELC Scheme

The ELC scheme consists of two control circuits:

a) Control Signal Generation

b) PWM Signal generation

Control Signal Generation

A logic circuit is developed that generates a HIGH signal whenever either symmetrical or any unsymmetrical fault occurs.

The RMS value of the actual phase currents is compared against the reference current of 200A. Whenever any of the rms value of phase currents exceed 200A, the output signal (CS) goes HIGH, thus, connecting the dummy load in the system.

This circuit ensures that the energy is dumped to dummy load only when there is a fault in the system.

PWM Signal Generation and working of the dummy load

The voltage across the dc link capacitor of the inverter, Vdc is compared against the reference voltage of 600V and fed to a PI Controller.

Here, the output of the PI Controller is restricted between 0 & 1 to make it compatible for duty cycle generation. So, whenever the Vdc is greater than the reference voltage, the errors signal is generated. This signal is fed to a Duty to PWM signal generator that generates an output PWM Signal that is directly proportional to the duty of the error signal. Finally, this PWM signal drives the IGBT diode.

According to the PWM signal, the diode turns ON and OFF and the conduction is varied. For the ON period of the IGBT Diode, the dummy load dumps the energy that reduces Vdc to a system standard value.

Thus, according to the grid codes, the PV system can stay connected to the grid as its voltage returns to the safe value within the specific time period. Here, our model satisfies the German EON Grid code which stipulates that the voltage after fault must recover to 0.9pu within 1.5 sec in order for the PV system to remain connected with its grid.

Calculation Of Ballast Load Resistance, R

From the graph, (Fig 9)

$Power_{peak} = 123.6kW$

Additional power to dump, $P_{add} = Power_{peak} - Power_{PV} = (123.6-50)kW = 73.6\ kW$

Ballast load resistance , $R = \frac{V^2}{P_{add}} = \frac{600^2}{73.6*10^{\wedge}3} = 4.89\ \Omega$

On optimizing based on simulation output, $R = 4.59\ \Omega$

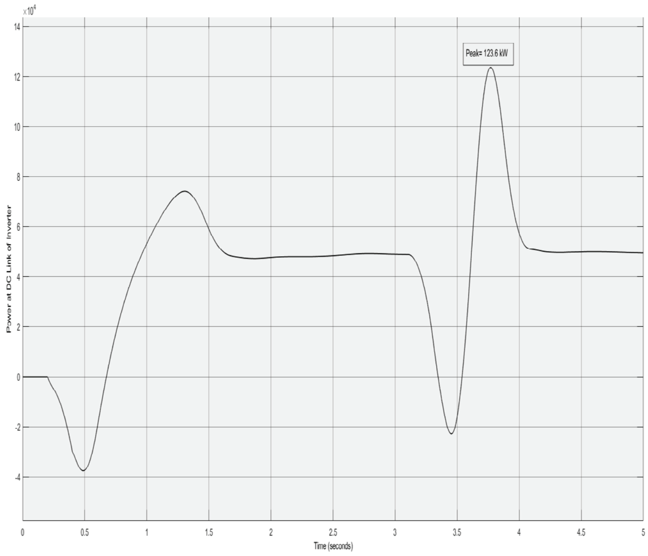

Fig 9 Plot of power at inverter DC link

It is to be noted that the dummy load resistance is calculated to dump the maximum possible energy during the fault.

Simulation & Development

The Simulink Modelling of the scheme is initiated in the MATLAB. The work is initiated by placing the PV array on the workspace of Simulink. The values of parallel string and series module is set as 25 and 5 respectively. Maximum power point tracking (MPPT) technique is with photovoltaic (PV) solar systems to maximize power extraction under all conditions. MPPT is coordinated with a DC-DC converter to get desired voltage at output terminal.

Then the inverter is introduced in the system for obtaining an AC supply for the connection with the grid. Three phase bridge is made with IGBTs. PWM signals are added to each gate signal and the output current of inverter is controlled by Hysteresis current control technique. Then the suitable values of resistance and inductance is chosen as a filter for the connection with the grid.

Initially, all the results are observed without any fault introduction.

Then the fault was introduced in different section of the grid connected PV system and the results were observed.

Simulation Result Study

After the simulation of the model, graphical representation of the results is studied. It is observed that the power of 50KW is injected to the grid and the DC voltage of 364 V is obtained at the PV side. Fig 10 and 11 show the terminal voltage curve of PV array and output power of PV array respectively.

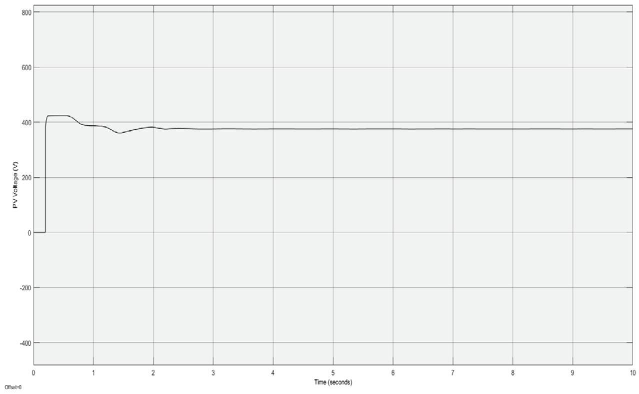

Fig 10 PV output voltage

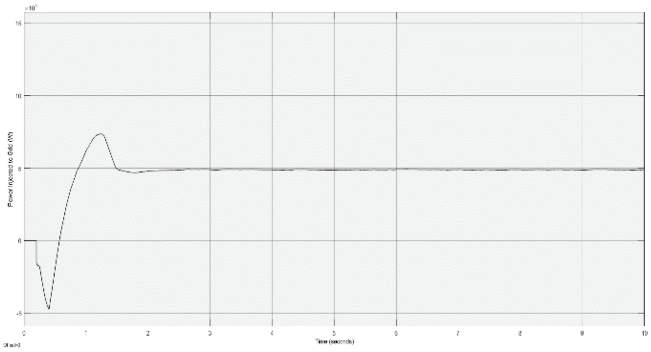

Fig 11 Plot of Power Injected to the grid

Then the voltage level of solar terminal is boosted up using a boost converter. Fig 12 shows the output voltage across the DC link capacitor which is obtained as 600V.

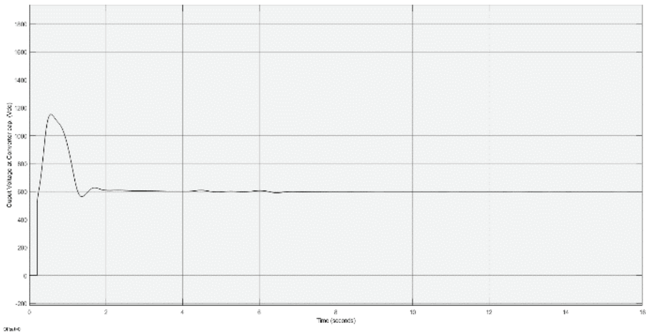

Fig 12 Plot of Vdc across the DC link capacitor

Similarly, the plot of actual current and reference current has also been generated. Fig 13 shows the tracking of current with respect to time and Fig 14 shows the waveform of phase voltage before RL filter.

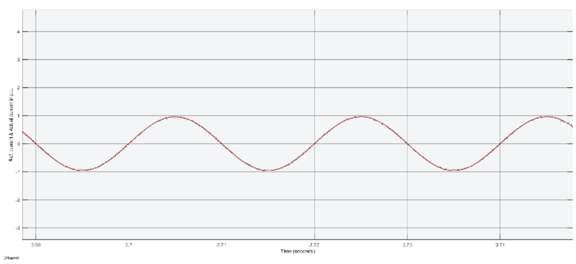

Fig 13: Actual and Reference Current Tracking

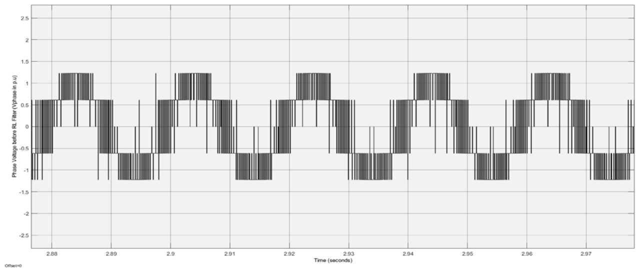

Fig 14 Plot of per phase inverter output voltage Before RL Filter

Then the single line to ground fault (from 3.1 to 3.4 sec) is introduced at the inverter side. Fig 15 shows the output voltage across the DC link capacitor. The voltage rises from 600V to about 1400V after the fault introduction which lasted from 3.1 to 3.4 sec.

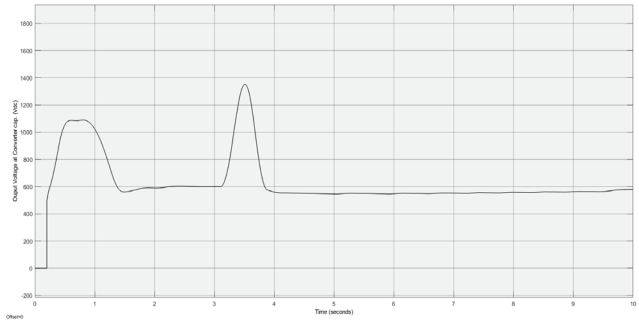

Fig 15 Plot of Vdc Rise During Fault

Similarly, the plot of actual current and reference current after the fault introduction has also been generated. Fig 16 shows the tracking of current with respect to time. It was observed that the actual current did not track the fault current once the line to ground fault was introduced.

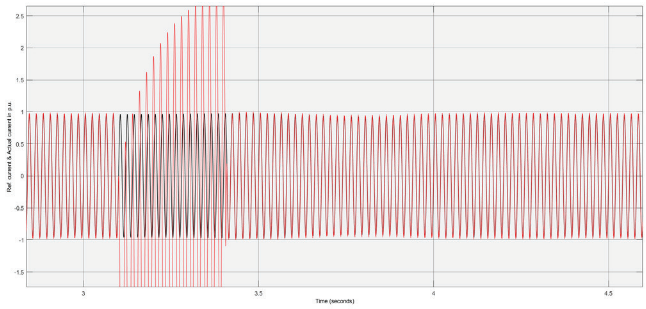

Fig 16 Current Tracking During Fault

After the fault is cleared, the tracking is proper and finely tuned.

Similarly, Fig 17 shows the waveform of voltage and current at the inverter side. During line to ground fault, voltage at the faulted phase is reduced to zero whereas the voltage at the other two healthy phases rises to about 1500 V. Similarly, in the Fig 18 the magnitude of current at the inverter output rises to a very high value of around 800 A from 3.1 to 3.4 sec

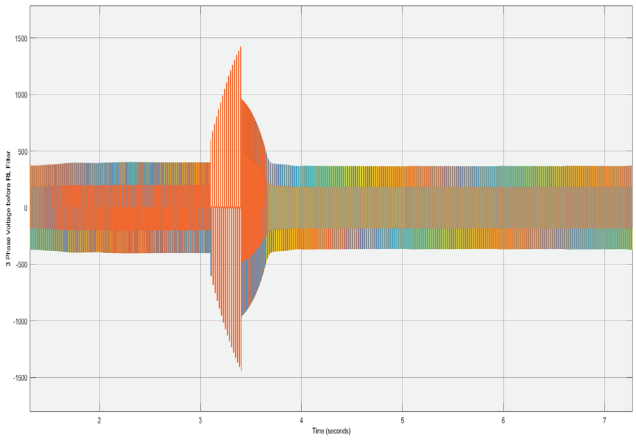

Fig 17 Three Phase Inverter Output Voltage

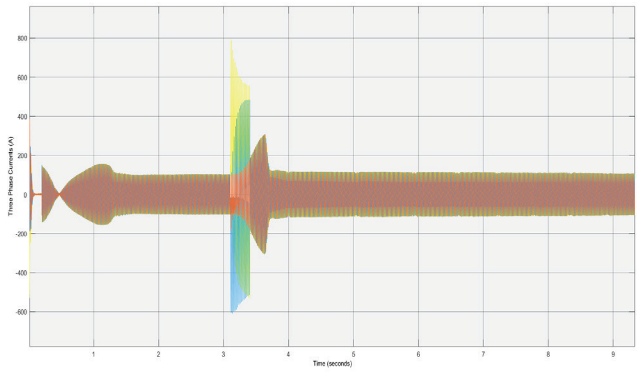

Fig 18 Three Phase Inverter Output Current

After the simulation of the model by introduction of single line to ground fault from 3.1 to 3.4 sec at the grid side, graphical representation of the results is studied. Fig 19 shows the output voltage across the DC link capacitor during the fault. It shows that even during the fault, the voltage across the capacitor is maintained at 600 V without any excessive rise in the voltage.

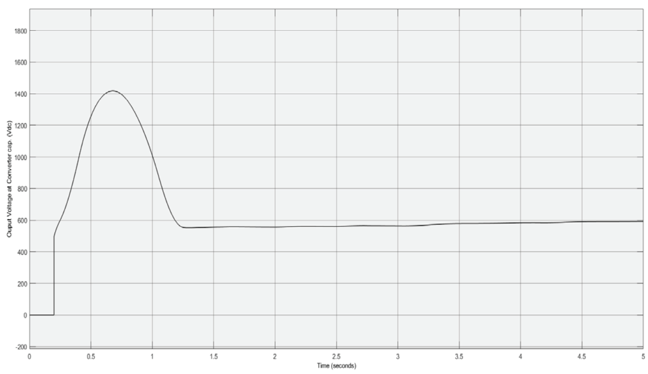

Fig 19 Plot of Output Voltage at Capacitor (Vdc)

Similarly, graphical representation of 3 phase balanced inverter current as well as proper current tracking even after the introduction of fault at the grid side has been shown in Fig 20 and 21 respectively.

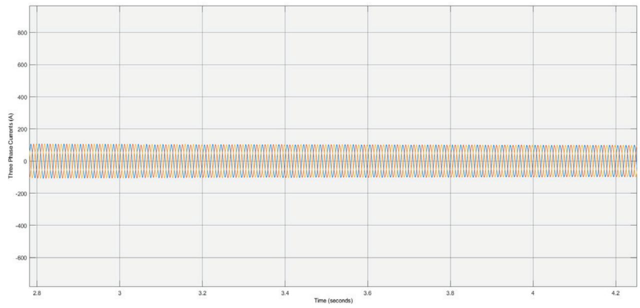

Fig 20 Plot of Three Phase Inverter Currents

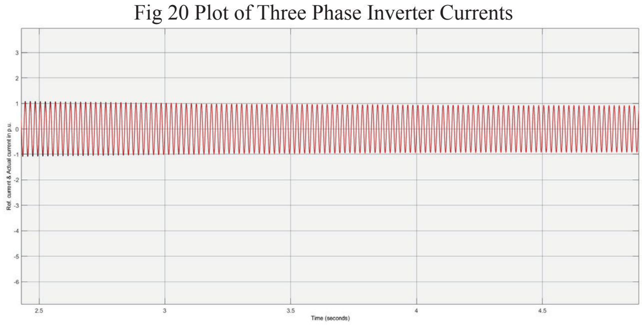

Fig 21 Plot of Current Tracking

So it is clear that the problem of overvoltage and overcurrent existed only when the single line to ground fault is introduced at the inverter side and not the grid side.

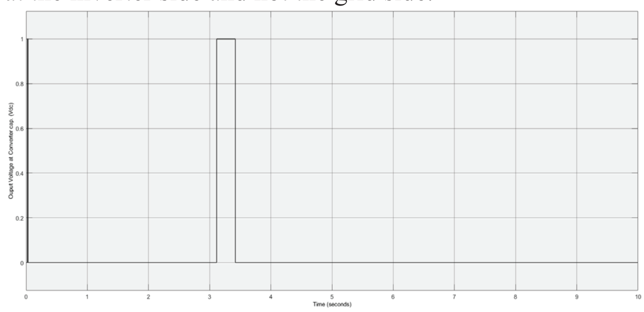

Fig 22 Plot of Control Signal of ELC

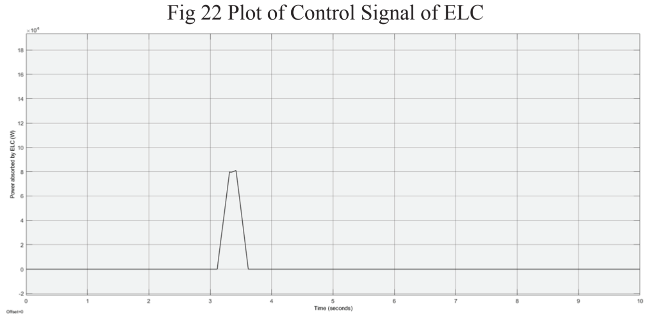

Fig 23 Plot of Power Dumped in ELC

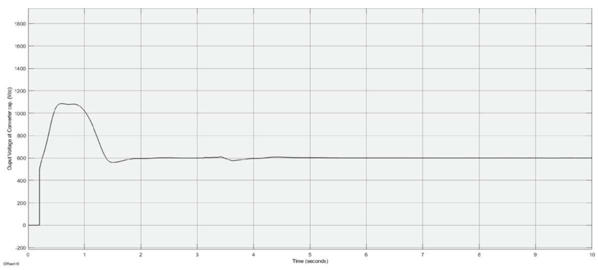

Fig 24 Plot of Vdc After Using ELC

Fig 24 shows the output plot after connection of ELC. During the fault condition from 3.1 to 3.4 sec, the control signal of ELC is set high and the power of about 80 kw is dumped in the resistive load. Thereby, the voltage across the dc link capacitor is successfully maintained at 600 V even during the fault condition after using ELC.

Conclusions

In this proposed scheme, grid-tied PV inverter has been successfully controlled during unbalanced transient fault. The effects of transient fault in different section of the grid connected PV system is studied and a control scheme to mitigate the over-voltage across the DC -Link capacitor is developed. Overvoltage during the transient fault which was about 1400 Volts is effectively reduced to 600 Volts with the introduction of ELC. By limiting this transient overvoltage, the current trend of shutting down the inverter in such cases is eliminated. By all counts, inverter is protected and continuity of supply is ensured.

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