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Performance Analysis of Voltage Source Inverter-Based Grid-Connected Photovoltaic Power Plants with Ride-Through Capability under Grid Faults

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***Abstract*—** The voltage source inverter (VSI) topology is widely used for grid interfacing of distributed generation (DG) system when employed in photovoltalic (PV) systems VSI normally required another single and two stage inverter to step up the voltage by adding to the cost and complexity of the system which makes the proliferation of grid connected pv systems which is an economically successful business option with respect to performance and life expectancy of the power electronic interfacing that need to be improved. The VSI in terms of inherent boosting and short circuit protection capability including the direct output current controlled and ac side simpler filter structure. The research on VSI based DG is still in its development stage where the paper focuses on modeling controlling and steady state transient performances of a PV system based on VSI by performance a comparative performance evaluation of VSI based PV system under transient and fault condition with the analytical expectations are being verified under different condition 1) excessive dc-link voltage; 2) excessive ac currents; and 3) loss of grid-voltage synchronization. In this paper, the control of single- and two-stage grid-connected VSIs in photovoltaic(PV) power plants is developed to address the issue of inverter disconnecting under various grid faults.

Index Terms*—DC–DC converter, fault-ride-through, photovoltaic (PV) systems, power system faults, reactive power support.*

I. INTRODUCTION

Fault studies are important in large scale grid connected renewable energy system has been reported in the technical literature most of the studies focused on grid connected wind power plant. In the case of grid-connected photovoltaic (PV) power plants (GCPPPs), research reported thus far focused on fault-ride through (FRT) capability Specifically, a three-phase current-source inverter (CSI) configuration remain limited under all types of faults due to the implementation of a current-source model for the inverter. Three-phase voltage source inverters (VSIs) are used in grid-connected power conversion systems. Due to the increasing number of these systems, the control of the VSIs is required to operate and support the grid based on the grid codes (GCs) during voltage disturbances and unbalanced conditions. In the application of GCPPPs with the configurations of single-stage conversion (single-stage conversion means direct connection of the PV source to the dc side of the VSI and the FRT issues of both ac and dc sides of the inverter under unbalanced voltage conditions. In the application of a two-stage conversion (meaning a dc–dc conversion or pre regulator unit exists between the PV source and VSI), no paper so far has proposed a comprehensive strategy to protect the inverter during voltage sags while providing reactive power support to the grid. All the designs and modifications for the inverter in both the single- and two-stage conversions have to accommodate various types of faults and address FRT capability based on the GCs. PV inverter disconnection under grid faults occurs due to mainly three factors: 1) excessive dc-link voltage; 2) excessive ac currents; and 3) loss of grid voltage synchronization, which may conflict with the FRT capability. The utilization of grid-connected photovoltaic (PV) systems is increasingly being pursued as a supplement and an alternative to the conventional fossil fuel generation in order to meet increasing energy demands and to limit the pollution of the environment caused by fuel emissions. The major concerns of integrating PV into grid are stochastic behavior of solar irradiations and interfacing of inverters with the grid. Inverters interfacing PV modules with the grid perform two major tasks—one is to ensure that PV modules are operated at maximum power point (MPP), and the other is to inject a sinusoidal current into the grid. In order to perform these tasks effectively, efficient stabilization or control schemes are essential. The two cascaded control loops consist of an outer voltage control loop to settle the PV array at the MPPT, and an inner current control loop to establish the duty ratio for the generation of a sinusoidal output current, which is in phase with the grid voltage. Linear controllers such as proportional-integral (PI) controller can provide satisfactory operation over a fixed set of operating points as the system is linearized at an equilibrium point As linear controllers for nonlinear PV systems affects all the variables in the system and the electrical characteristics of the PV source are time varying, the system is not linearized around a unique operating point or trajectory to achieve a good performance over a wide variation in atmospheric conditions. The restrictions of operating points can be solved by implementing nonlinear controllers for nonlinear PV systems Feedback linearization has been increasingly used for nonlinear controller design. It transforms the nonlinear system into a fully or partly linear equivalent by cancelling nonlinearities. In this paper, the control strategy introduced in for a single-stage conversion is used, although the voltage sag detection and reactive power control is modified based on individual measurements of the grid voltages.

II. CASE STUDY FOR A SINGLE-STAGE CONVERSION

In this section, a 1-MVA single-stage GCPPP is considered. It is modeled using MATLAB/Simulink and the system main specifications are summarized in Table I from the data given in. In, concerning the FRT capability, the inverter disconnection factors are illustrated according to the GCs.

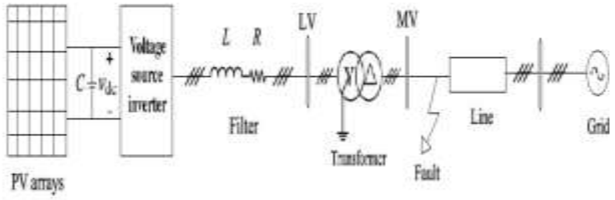

Figure 1 Block Diagram of Single Stage Conversion

TABLE 1. CASE STUDY SYSTEM SPECIFICATIONS

PV module specifications		PV inverter specifications	
Maximum operating voltage (V_{mpp})	35.6 V	Maximum dc power	1133 kW
Maximum operating current (I_{mpp})	8.29 A	Maximum dc input voltage	1000 V
Open circuit voltage (V_{oc})	44.3 V	Rated dc voltage	800 V
Short circuit current (I_{sc})	8.74 A	Apparent power rating (at STC)	1100 kVA
Number of parallel modules, n_p	155	**Filter**	$R = 1$ mΩ $L = 150$ μH
Number of series modules, n_s	22	**Transformer**	1.2 MVA 20/0.415 kV Dyn11 50 Hz

A. Grid Voltage Synchronization

In grid-connected inverters, one important issue is the voltage phase angle detection. This is usually performed by phase locked- loop (PLL) technique based on a synchronous reference frame PLL (SRF-PLL), known as conventional PLL. The conventional PLL configuration does not perform well under unbalanced voltage sags and consequently may lead to the inverter being disconnected from the grid.

Several methods were proposed to extract the voltage phases accurately under unbalanced voltage conditions. In this paper, the method based on moving average filters (MAFs) introduced by applied, which was also used in showing very satisfactory performance. In this method, the positive sequence of the voltage is extracted from the grid by means of an ideal low-pass filter. Then, the angle of the positive sequence is detected.

B. Excessive AC Current

Commercial grid-connected inverters have a maximum ac current value specified. If any of the currents exceed such value, the inverter is disconnected from the grid. Under a grid voltage sag, the d-component of the current (in the SRF) increases because the controller wants to maintain the active power injected into the grid and grid voltages are temporarily reduced. In addition to the increase of the d current component, the inverter has to inject reactive current during the fault to meet the FRT requirements. The amount of reactive current is assigned according to the droop control given in (1). Since the d and q current components increase, this may lead the over-current protection to disconnect the inverter from the grid. In this case study, according to the specifications of the PV modules and their numbers of being connected in series and parallel given in Table I, the maximum power injected under standard test conditions (STC) is 1.006 MW. This power gives a rated rms current value of 1399.5 A (a peak value of 1979 A) at the low-voltage (LV) side of the transformer considering 100% efficiency for the GCPPP. According to the the inverter datasheets, the maximum acceptable output current at the LV side of the transformer is 1532 A (a peak value of 2167 A). In the case of a fault, e.g., a single-line-to-ground (SLG) voltage sag at the MV side of the transformer as the one presented in Fig. 3, the output currents exceed the limits. This will lead to should be mentioned that all the voltage sag case studies in this paper are applied to the MV side for the time period t = 0.1 s to t = 0.3 s, whereas the resultant ac voltages and currents shown in the figures are presented with their equivalent magnitudes at the LV side. Fig. 5 shows the generated currents after applying the current limiter in this example. One can observe in Fig. 5(b)

that the grid currents are balanced. This is because the active current reference (idref) is limited to an almost constant value during the voltage sag. It should be mentioned that when operating with low solar radiation and/or small voltage sags, the active current reference may not be limited and therefore, it goes through the current limiter without being affected, i.e., idref = i_ dref . As a consequence, if the voltage sag was unbalanced, the active current reference and consequently the output currents would contain some low-frequency harmonics.

C. Excessive DC-Link Voltage

If the active current reference is limited, i.e., idref < i_ dref , the generated power from the PVs is more than the injected power into the electrical grid. As a consequence, some energy is initially accumulated into the dc-link capacitor, increasing the dc bus voltage as shown in Fig. 5(c). In a single-stage GCPPP, as the dc-link voltage increases, the operating point on the I−V curve of PV array moves toward the open-circuit voltage point (Voc), which leads the PV current to decrease, as shown in Fig. 6. The power generated by the PV panels is reduced because the operating point is taken away from the maximum power point (MPP) and therefore, less active current is injected into the ac side. This happens until the GCPPP reaches a new steady state where the dc-link voltage stops increasing. Thus, single-stage GCPPPs are self-protected because the generated power is reduced when the dc-link voltage increases under ac faults. It should be mentioned that the inverter has to withstand the worst case of the dc-link voltage, which is produced when the voltage provided by the PV modules reaches the open-circuit value (Voc) under the maximum solar radiation expected on the generation site. Hence, the number of PV modules connected in series (ns) has to be limited in the design of the GCPPPs so that the dc-link voltage is never higher than the maximum acceptable value of the inverter

III. CASE STUDY FOR A TWO-STAGE CONVERSION

A two-stage GCPPP includes a dc–dc converter between the PV arrays and the inverter. In high-power GCPPPs, more than one dc–dc converter can be included, one per each PV array. Despite having several dc–dc converters, these systems will be referred anyway as two-stage GCPPPs. In two-stage GCPPPs, the MPP tracking (MPPT) is performed by the dc–dc converter and the dc-link voltage is regulated by the inverter. During a voltage sag, if no action is taken in the control of the dc–dc converter, the power from the PV modules is not reduced and therefore, the dc-link voltage keeps rising and may exceed be the maximum limit. Hence, the system is not self-protected during grid fault conditions. A specific control action has to be taken to reduce the power generated by the PV modules and provide the two-stage GCPPP with FRT capability.

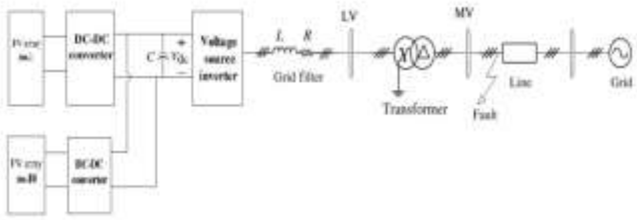

Figure 2 Block Diagram of Two Stage Conversion

A simple method to provide dc-link overvoltage protection consists on shutting down the dc–dc converter when the dc voltage rises above a certain limit. The dc–dc converter can be reactivated when the dc-link voltage is below a certain value using a hysteresis controller. In the solutions proposed in this paper, the dc-link voltage is controlled during the voltage sag process and there is no significant increase in the dc-link voltage during this transient. The diagram of the case study for a two-stage GCPPP is shown in Fig. 9. It consists of a 1-MVA inverter and 10parallel100-kW dc–dc boost converters. Details of the individual dc–dc converter as well as the PV array characteristics connected to each dc–dc converter are summarized in Table II. The rest of data for this system are provided in Table I. dc-link voltage under fault conditions are proposed: 1) short circuiting the PV array by turning ON the switch of the dc–dc converter throughout the voltage sag duration; 2) leaving the PV array open by turning OFF the switch of the dc–dc converter; and 3) changing the control of the dc–dc converter to inject less power from the PV arrays when compared with the pre fault operating conditions. It should be mentioned that in all the configurations including single-stage conversion, the MPPT is disabled during the voltage sag condition and the voltage reference of pre fault condition (Vmpp) is considered. Once the fault ends, the MPPT is reactivated. In the two-stage topology, the first two solutions explained next stop transferring energy from the PV arrays to the dc bus, whereas the dc bus keeps regulated at the reference value by the voltage control loop.

TABLE II

DC–DC converter and PV array specifications			
Input voltage of the dc–dc converter at MPP, V_{PV}	356 V	Output voltage of the dc–dc converter, V_{dc}	800 V
Number of parallel PV modules in each array, n_p	34	DC–DC converter inductance, L_i	1 mH
Number of series PV modules in each array, n_s	10	DC-link capacitance, C	31 mF

In two-stage GCPPPs, the PV voltage (vpv) is controlled by the duty cycle (d) of the dc–dc converter. The reference for the PV voltage is given by the MPPT, as shown in Fig. 10. A feed-forward strategy is applied to improve the dynamics of the dc-link voltage. The strategy is based on the assumption that the PV generated power is equal to the injected power into the grid, i.e.,

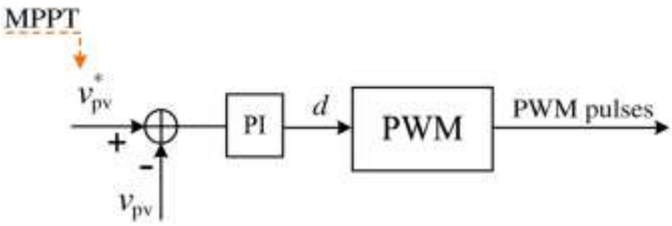

Figure 3 Block Diagram of MPPT

where ipv and vpv are the PV current and voltage, respectively, and ed and eq are the d and q grid voltage components extracted by the PLL. Since the PLL forces the eq component to be zero, the estimated d current component is obtained as in two-stage GCPPPs, three different ways to limit the dc-link voltage under fault conditions are proposed: 1) short circuiting the PV array by turning ON the switch of the dc–dc converter throughout the voltage sag duration; 2) leaving the PV array open by turning OFF the switch of the dc–dc converter; and 3) changing the control of the dc–dc converter to inject less power from the PV arrays when compared with the pre fault operating conditions. It should be mentioned that in all the configurations including single-stage conversion, the MPPT is disabled during the voltage sag condition and the voltage reference of pre fault condition (Vmpp) is considered. Once the fault ends, the MPPT is reactivated. In the two-stage topology, the first two solutions explained next stop transferring energy from the PV arrays to the dc bus, whereas the dc bus keeps regulated at the reference value by the voltage control loop. In the third method, the MPPT is disconnected and the PV operating point moves to a lower power level to avoid overvoltage in the dc-link. Therefore, no matter the MPPT technique is voltage or current controlled and the algorithms implemented for the MPPT, the performance of the proposed methods during the voltage sag condition remains the same because the MPPT is disconnected during the voltage sag.

A. Short-Circuiting the PV Panels

In this method, the dc–dc converter switch is ON (d = 1) throughout the voltage sag, as shown in Fig. 11. Consequently, no power is transferred from the PV modules to the dc-link. Since vpv is zero, the feed-forward term id−est in (5) defines a fast transition to zero at the beginning of the voltage sag, accelerating the overall dynamic of the controller. Fig. 12 shows some results for an SLG voltage sag with a 60% voltage drop at MV side occurred from t = 0.1s to t = 0.3s. The generated power of the PV arrays and also the injected active and reactive power into the grid are shown in Fig. 13. During the voltage sag, the dc-link voltage remains relatively constant, idref becomes almost zero with some ripples, and only iqref is injected during the fault period. Consequently, the current limiter does not have to be activated in this case. Under unbalanced voltage sags, the output power contains a second-order harmonic, which will produce dc-link voltage ripples at the same frequency.

B. Opening the Circuit of the PV Panels

Another option to avoid transferring power from the PV modules to the dc-link is to keep the dc–dc converter switch Since, the inverter is not transferring active power into the grid during the voltage sag, the PV voltage vpv increases until the dc–dc converter inductor is completely discharged (ipv = 0).Then, the diode turns OFF and the PV modules stop providing energy into the dc-link. This case is similar to the previous one where the diode was continuously ON and no current from the PV was provided to the dc-link.

C. Injecting Less Power From the PV Panels

In the two previous cases, during the voltage sags, there is no power generated by the PV panels and therefore, only reactive current is injected into the grid. However, as mentioned in, the network operator is allowed to feed the grid through the generating power plant during the voltage sags. For this purpose, the GCPPP is controlled to inject less power into the grid during the voltage sag compared with the pre fault case, while avoiding overvoltage in the dc-link. In normal operation, the MPPT function is performed by the dc–dc converter, whereas the dc-link voltage is regulated by the inverter. However, under voltage sag, some modifications should be implemented in order to keep the GCPPP grid-connected. The proposed method tries to match the power generated by the PV modules with the power injected into the grid while trying to keep the dc-link voltage constant. Unlike the previous cases of keeping the switch ON or OFF during the voltage sag, in this case, power balance is achieved for a value different from zero. Therefore, both active and reactive currents will be injected into the grid. In the proposed method, the target of the dc–dc converter is no longer achieving MPP operation but regulating the power generated by the PVs to match the maximum active power that can be injected into the grid. The dc–dc converter is controlled to find a proper value for the PV voltage (vpv) that achieves such power balance. As a result, the operating point should move from point A in Fig. 16 to a lower power point, e.g., either the points B or C. In this paper, moving the operating point in the direction from A to B is applied and analyzed.

IV.MAXIMUM POWER POINT TRACKING

The current-voltage behaviour of solar panels nonlinearly depends on the solar irradiation intensity and environmental temperature. If increase in sun irradiation level and decrease in ambient temperature result in a higher output current and voltage Consequently, the environmental condition variations change the maximum output power of solar panels In the grid-connected PV system, the DC link capacitor is chargedby solar array, and then power is switched out from the capacitor using the power converter and the extracted power is injected to the utility grid. To ensure that solar arrays deliver maximum available power to the converter an interface device between converter and PV panels needs to be employed to control the flow of power. Bruntonet al. have pointed out that: “As irradiance decreases rapidly, the I-V curve shrinks and the MPV and MPI decrease. If the MPPT algorithm does not track fast enough, the control current or voltage will fall off the I-V curve.” The MPPT techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change A MPPT is used for extracting the maximum power from the solar PV module and transferring that power to thegrid. MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion, filtering, and regulation for driving various loads, including power grids, batteries, or motors.

4.2 MPPT TECHNIQUE

The peak power point tracking techniques vary in many aspects, such as: simplicity, convergence speed, digital or analog implementation, sensors required, cost, range of effectiveness etc. The MPPT implementation topology greatly depends on the end-users’ knowledge Inanalog world, short current (SC), open voltage (OV), and temperature methods (tempe rature gradient (TG) and temperature parametric equation (TP)) are good options for MPPT, otherwise with digital circuits that require the use of micro-controllers, perturbation and observation (P&O), IC (incremental conductance), and temperature methods are easy to implement.Table 4.1 present the comparison among differentMPPT methods considering the costs of sensors, micro-controller and the additional power components.In this table, A means

MPPT Algorithm	Additional Compo-nents	Sensors	Micro-Controller	Total
CV	A	L	A/L	L
SC	H	M	A/L	M
OV	H	L/M	A/L	L/M
P&Oa	A	M	L	L/M
P&Ob	A	M	L	L/M
P&Oc	A	M	M	M
IC	A	M	M	M
TG	A	M/H	M	M/H
TP	A	H	M/H	H

Table 4.1: Comparison of MPPT algorithms.

Currently, the most popular and the workhorseMPPT algorithm is perturb and observe(P&O), because of its balance between performance and simplicity.

4.2.1 PERTURB AND OBSERVE METHOD

Currently the most popular MPPT method in the PV systems is perturb and observe. In this method, a small perturbation is injected to the system and if the output power increases, a perturbation with the same direction will be injected tothe system and if the output power decreases, the next injected perturbation will be in the opposite direction. The scheme of P&O method is presented in P&O algorithm requires few mathematical calculations which makes the implementationof this algorithm fairly simple. For this reason, P&O method is heavily used inrenewable energy systems.[RES] However, the P&O algorithm is not able to distinguish the differencebetween the system perturbations (e.g. voltage regulation variations or environmentalcondition variations) and injected perturbation from P&O, and therefore it may make a wrong adjustment as the result, especially in the presence of rapid system variations. Moreover, in the steady state operation, the power oscillates around the maximum power point, therefore the system can potentially jump to undesirable or even unstable modes. This phenomena is another disadvantage of P&O method. Recently, a new adaptive control scheme, called extremum seeking control,Recently, a new adaptive control scheme, called extremum seeking control, has been developed. In this method, the sign of last perturbation and the sign of the last increment in the power are used to decide.In the left of the MPPT incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power.If there is a increment in the power, the perturbation should be kept in the same direction and if the power decreases, then next perturbation should be in the opposite direction. Based on these facts, the algorithm implemented.The process is repeated until the MPPT is reached. Then the operating point oscillates around theMPPT.

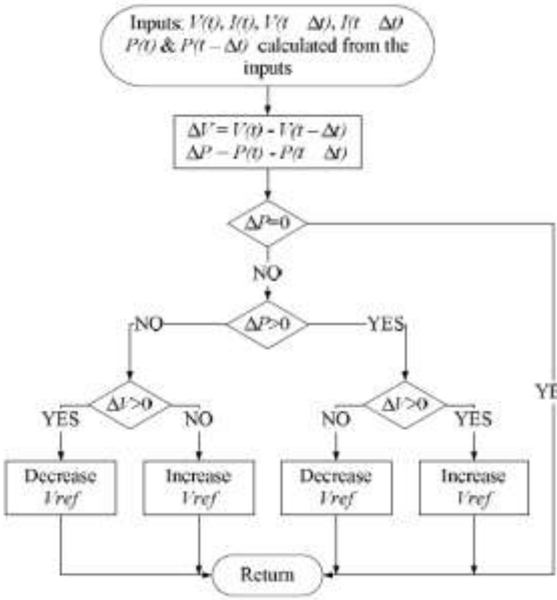

Figure 3 P&O Algorithm Flochart

V. SIMULATION MODEL AND RESULTS

The basic PV system is modeled based on the equation in equivalent circuit of the PV cell. In this project totally ten panel are made with the range of 4,7A 25.04V 117.07W of each panel Perturbation & Observation (P&O) MPPT technique are used in this project to extract maximum power under changing atmospheric condition Boost converter are used to boost up the PV output voltage to synchronize the inverter to the grid

A. Grid Voltage Synchronization

In grid-connected inverters, one important issue is the voltage phase angle detection. This is usually performed by phase locked- loop (PLL) technique based on a synchronous reference frame PLL (SRF-PLL), known as conventional PLL. Several methods were proposed to extract the voltage phases accurately under unbalanced voltage conditions . In this method based on moving average filters (MAFs) introduced is applied, which was also used very satisfactory performance. In grid-connected inverters, one important issue is the voltage phase angle detection.

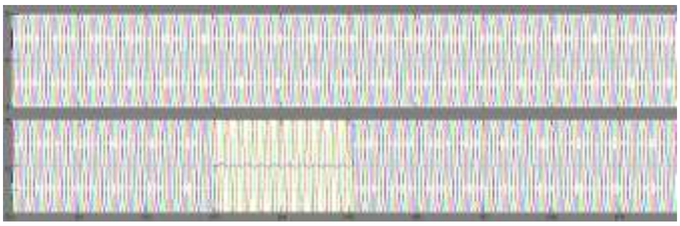

Figure 4 Output Waveform Of Grid Voltage Synchronization

B. Excessive AC Current

Commercial grid-connected inverters have a maximum ac current value specified. If any of the currents exceed such value, the inverter is disconnected from the grid. In this case study, according to the specifications of the PV modules and their numbers of being connected in series and parallel given in Table I, In the case of a fault, e.g., a single-line-to-ground (SLG) voltage sag at the MV side of the transformer as the one presented in Fig. 3, the output currents exceed the limits.

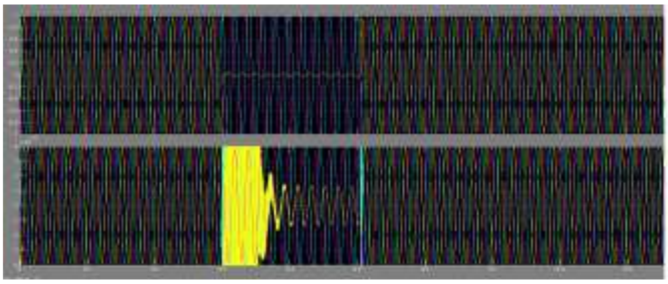

Figure 5 Output Waveform Of Excessive AC Current

C. Excessive DC-Link Voltage

If the active current reference is limited, i.e., idref < idref , the generated power from the PVs is more than the injected power into the electrical grid. In a single-stage GCPPP, as the dc-link voltage increases, the operating point on the I−V curve of PV array moves toward the open-circuit voltage point (Voc), which leads the PV current to decrease

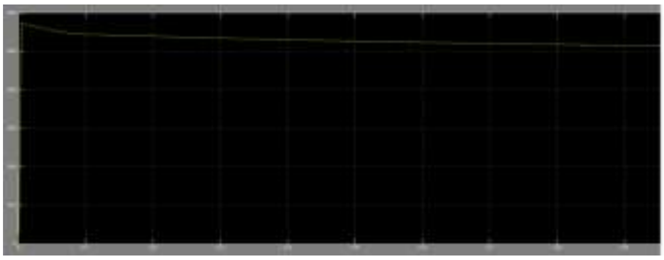

Figure 6 Output Waveform Of Excessive DC-Link Voltage

VI.CONCLUSION

Performance requirements of GCPPPs under fault conditions for single- and two-stage grid-connected inverters have been addressed in this project. Some modifications have been proposed for controllers to make the GCPPP ride-through compatible to any type of faults according to the GCs. These modifications include applying current limiters and controlling the dc-link voltage by different methods. It is concluded that for the single-stage configuration, the dc-link voltage is naturally limited and therefore, the GCPPP is self-protected, whereas in the two-stage configuration it is not. Three methods have been proposed for the two-stage configuration to make the GCPPP able to withstand any type of faults according to the GCs without being disconnected. The first two methods are based on not generating any power from the PV arrays during the voltage sags, whereas the third method changes the power point of the PV arrays to inject less power into the grid compared with the pre fault condition. The validity of all the proposed methods to ride-through voltage sags has been demonstrated by multiple case studies performed by simulations

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