

Reactive Power Control Strategy for Single-Phase Grid-connected PV System

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Abstract— Provided that production and deployment of PV systems continues to grow at extraordinarily fast rate, applicable grids management policy should gradually adjust advice to allow increasingly PV systems to be deployed in the grid. A next-generation PV system, such as what traditional power plants do today, would then perform a much significant role in grid regulation engagement. In certain countries provision of ancillary facilities such as voltage assistance via control of reactive power and Low Voltage Ride-Through (LVRT) combined with injection of reactive current has been in place. Such innovative technologies will be offered by PV systems of the next-generation and will be enhanced throughout the coming years to allow substantially better use through PV systems. Keeping that in mind, this paper presents a Reactive Power Injecting strategy in LVRT operating mode for single-phase PV systems. MATLAB / Simulink software simulates an exact description of the single-phase grid connected PV system. Simulations outcomes show the efficacy and feasibility of proposed strategy along with the control of reactive power throughout LVRT service.

Keywords— *Reactive power injection (RPI), Photovoltaic (PV) system, Low Voltage Ride Through (LVRT), Point of common coupling (PCC), Phase Locked Loop (PLL), Maximum Power Point Tracking (MPPT).*

I. INTRODUCTION

The rapid growth of advanced power electronics technology has shown tremendous promise for grid incorporation of renewable energies. As powered by an imperative demand for safe and efficient generation of electricity, the degree of penetration of PV systems is booming uninterruptedly [1]-[11]. It allows the dispersed networks extremely decentralized and insecure, thus requiring advanced control techniques to appeal to heavy grid penetration in the next generation Photovoltaic networks. Many other countries and international bodies are taking action in the manner of grid specifications or regulations that allow PV systems to avoid energizing regional loads in the face of irregular grid circumstances, such as voltage drops and fluctuations in frequency [2]-[6]. These grid management requirements are true as the PV systems still dominate residential markets and account for only a limited proportion of total electricity production in many other countries relative to other renewable systems, such as wind turbines system. The latest policies developed by feeds in tariff has

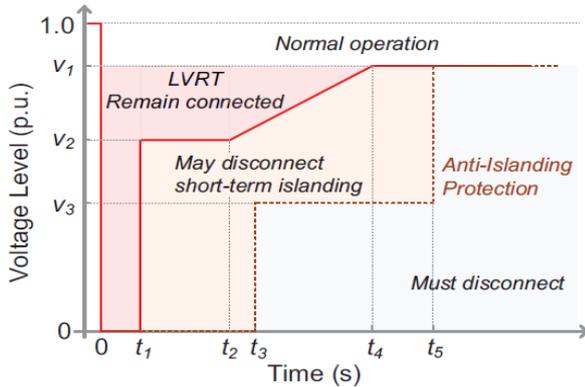
been providing long term contracts to renewable energy suppliers, motivating them to increase production of those technologies. Among all those technologies, solar energy has been awarded a higher per-kWh price which led to a significant increase in deployment of Grid connected Photovoltaic system. To satisfy needs of the power grids, improved control methods are required which could increase the system's reliability. In recent years, the function has been established. The key constraint of a PV system's grid and control methods for meeting those requirements are addressed in this section. Throughout grid abnormalities, Photovoltaic generators have not been conventionally permitted to remain attached to network. Therefore, they were unable to take part in system development throughout a fault state. Nowadays, due to the rising absorption of photovoltaic systems, they have to satisfy the functional requirement needed to manage their system is stable. In case of an interruption, individuals would not only be willing to remain aligned to grid, but should also assist the grid via the RPI throughout a steady state situation that contributes to voltage regulation as well as insertion of short circuit current throughout a fault situation.

In low-voltage Photovoltaic applications, single-phase systems are often more prevalent (e.g. multiple kilowatts) but are usually attached to low-voltage systems. Furthermore, for MPPT (Maximum Power Point Tracking) control in these grid regulations, most systems need to work with closed to unit power factor to generate that much electricity as feasible from PV panels [3]-[5],[7]-[9]. However, the growing implementation of Photovoltaic systems still presents so much daunting problems for distributed network operators and the distributed grid as a whole. On instance, the distributed feeders may display potential overloading impacts, particularly if a really higher Photovoltaic system penetration level has reached [6],[10]. Because of the irregular nature of the solar Photovoltaic generator as well as the imbalanced in both load demands and photovoltaic supply, voltage increases have been noticed primarily in latest research [6],[11]-[15].

By minimizing the overall power supply from Photovoltaic system or increasing the penetration of PV into the grid, another prospect could be accomplished to minimize voltage increases. These strategies, however, run counter to the aim for carbon mitigation in Europe, & especially in Germany and Italy, through making it possible to implement renewable energies ever more widely. In all of those countries

at which photovoltaic systems start taking up a significant portion with power generation, relevant grid specifications for the reactive power compensation were then put out. Those grid codes indicated that Photovoltaic systems could use reactive power control [16] to engage in voltage control.

Fig.1. Suggestion to implement LVRT & anti-islanding specifications



compatible with single-phase Photovoltaic systems.

In the meantime, due to the anti-islanding protection provided by current grid codes, accidental trip-off of large quantities of Photovoltaic system would also cause frequency fluctuations [6],[15] going to lead toward more severe cases such as power outages as well as voltage flickers. Hence, the active power deduction would be used for frequency assistance for Photovoltaic system. Some other characteristic relating to Photovoltaic system with reaction to grid abnormalities is the potential to afford vibrant grid assistance as the Reactive Power Injection (RPI) and LVRT.

These grid specifications are also useful in certain countries for: a) maintain the grid in the event with faults; & b) prevent the damage of major Photovoltaic generation system due to transitory voltage of grid. For example, each and every generation system having output of more than six kilowatts must have LVRT functionality in Italy. Many nations continue to revise the grid code to allow for more grid PV systems [6], [17]-[18]. The LVRT feature design breaches the anti-islanding needs. Thus, can be seen in figure 1, while improving grid specifications, attention should be given to the efficiency of these two roles.

Nevertheless, as penetration levels continue to develop, grid specifications for Photovoltaic systems should therefore be strengthened, becoming stricter and more precise to ensure stable and effective power generation with lower energy costs. This is healthier to provide a reactive power management feature for the next generation of Photovoltaic system to assist statically and even dynamically ride-through failures in the grid voltage, that is compatible with Reactive power injection control all through the transients.

This paper suggests a robust reactive power injection technique that helps the grid-connected Photovoltaic system to work under ordinary operation and the grid failure state. Such an instruction would be rendered using PI controllers in voltage and current regulate loops within the d-q reference frame. In standard operating mode, the instruction established

current and voltage loops were constructed to regulate the output inverter current and the dc-link voltage, respectively. A control method computes interactively, in grid Fault Operating Mode, active as well as reactive power which the inverter will deliver if voltage dips occur as of the PCC. The reference inverter currents are determined using those values. This suggested method defeats limitations like unsafe dc-link voltage, current harmonics, current peak as well as maintains as long as possible a stable connection to the grid.

II. SYSTEM DESIGN AND POWER CONTROL DESCRIPTION

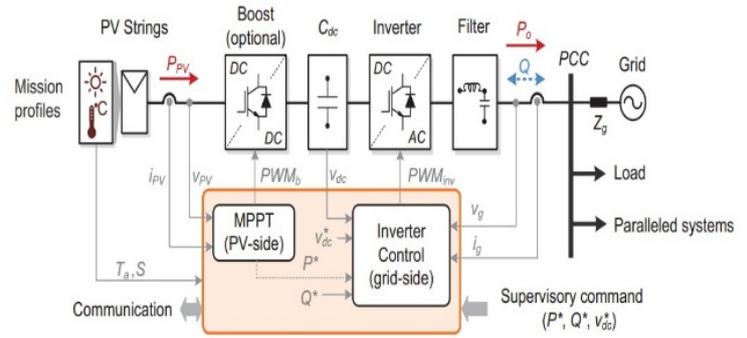


Fig.2. Standard control scheme of grid-connected Photovoltaic system.

Regarding use of the RPI function to control single-phase systems, an option is based on the concept of droop [9], which generally allows the line to be mainly inductive. However, the single-phase distributed line has a low X / R ratio and is mainly resistive. Therefore, although the use of adaptive filtering techniques contributes to instantaneous control of power solutions [16], there is no use of the droop control approach for photovoltaic systems that used implement RPI functions. This power control approach is a good option for single-phase systems when a proper description of the power reference is obtained.

This document presents the two main operating modes of the photovoltaic system connected to the proposed network: the normal operating mode and the operating mode of grid failure. The recommended control measures can be implemented in the form of reference curves in normal operating mode and around the inverter on the grid side, by configuring the reference power (reactive power (Q *) and active power (P *)). The active power reference value is nearly equivalent to the maximum photovoltaic power, and the reactive power reference value will be zero, so that the grid current and grid voltage remain in phase. Regulation of active power is achieved through adjusting the voltage of the DC bus.

Because of its simplicity and its cheaper implementation, in order to obtain the maximum photovoltaic power, traditional MPPT perturbation and observation algorithm was implemented into first stage. If the PCC detects a decrease in grid voltage, the inverter will automatically increase the current output to maintain a balance of power between the grid and PV generator. The current is therefore constrained by

the inverter's nominal current. At the same time, the inverter will inject reactive power which varies with the degree of voltage decrease, which would be the maximum inverter current requirement indicated by references [16]. To protect the bus capacitor and maintain a steady DC bus voltage, the power provided through the Photovoltaic generator must be equivalent to the inverter's output power.

A. Power Control on PV-Side

The MPPT algorithm is used with the photovoltaic generator, depending on the method of perturbation and observation (P&O). Its objective would be to obtain maximum output of photovoltaic generator under all operating conditions as a function of the irradiation and the temperature. The operating principle of this MPPT technique is illustrated in Figure 3. Intentionally "disturbing" operating voltage of the

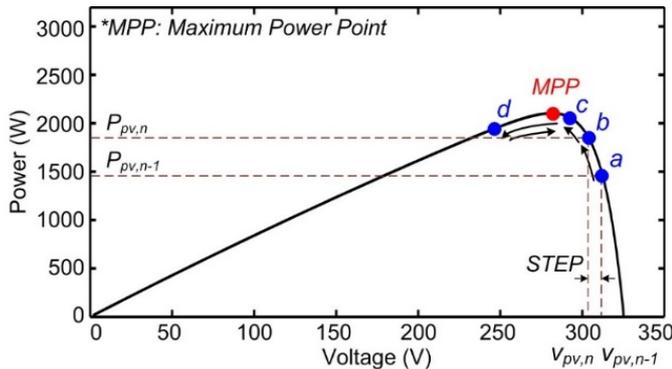


Fig.3. Concept of Perturb and Observe MPPT Algorithm.

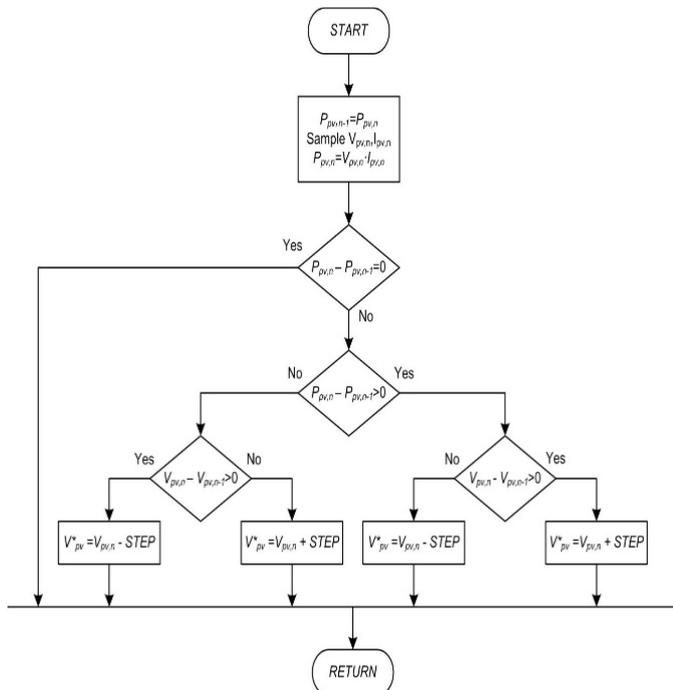


Fig.4. Perturb and Observe MPPT algorithm flow diagram.

photovoltaic generator V_{pv} , then "observing" the difference in the photovoltaic generator output power to determine location

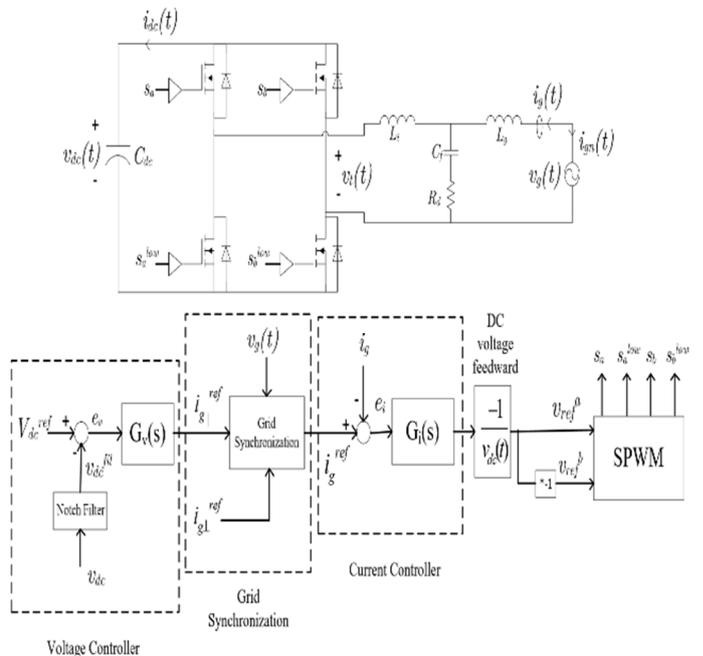
of next disturbance. If the disturbance V_{pv} leads to an improvement in the output power P_{pv} , the following disturbance (i.e. $a \rightarrow b \rightarrow c$) must be followed in the same direction. Otherwise, if the increase in V_{pv} leads to a decrease in P_{pv} (i.e. $c \rightarrow d$), the perturbation will reverse the direction [19].

The flow diagram of the P&O MPPT algorithm is illustrated in Figure 4, where $I_{pv,n}$ and $V_{pv,n}$ are the measured current and the voltage of the current sample, which can be combined to produce the PV output power $P_{pv,n}$. Likewise, the previously sampled calculated voltage and current are $I_{pv,n-1}$ and $V_{pv,n-1}$ and the previously sampled PV output power is $P_{pv,n-1}$. STEP is the disturbance step and V_{pv}^* is the reference Photovoltaic voltage.

Once reaching the MPP, the power of the PV output oscillates in the MPP. This unavoidable oscillation in the PV systems will cause power loss and is among the major drawbacks of the P&O MPPT algorithm. A smaller step size should be selected to reduce the oscillation. In general, the P&O MPPT technique could be used as a reference either for the V_{pv}^* PV output voltage or the I_{pv}^* current. The reference voltage supplied by the MPPT algorithm represents input of the current and voltage controller.

B. Power control on Grid-side

The inverter directive targets to transfer the energy created by the solar power generators to customized, controlling the voltage of dc-bus and to introduce less THD currents under unit power factor. Inverter control can also be split into three subgroups: Current control, grid synchronisation, and DC voltage control. A schematic diagram for controllers is given in Fig.6. Voltage regulator preserves the desired quantity of DC voltage whilst the current



controller handles the current infusion into the system. It is not possible to control the reactive power and the active power

of the single-phase VSI by controlling the I_d and I_q values in the d-q reference frame.

Grid-Side Power Controllers. Grid-connected inverter [21] typically employs two cascaded control loops. The outside loop regulates the power pumped into the grid by means of the voltage regulation of DC-link. The internal loop is really current controller that also controls power quality problem as well as requires to aim better than that of the external power loop [21]. The external power loop contains different methods of regulation, depending on the model. The DC-link voltage controller shown here in Fig.5 also is one generally employed control system.



Fig.6. Inverter controller block structure.

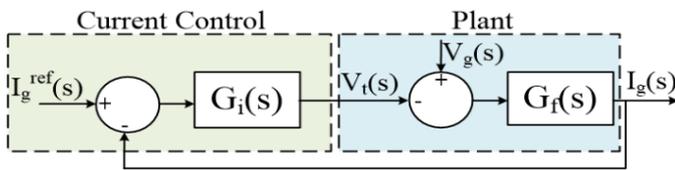


Fig.7. Current controller block representation.

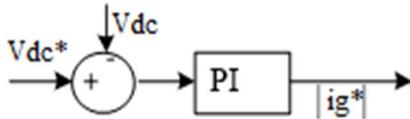


Fig.8. Voltage regulator block diagram.

Current Controller. The existing picture of fig.7 is of controlling the internal current loop. The current controller uses Proportional Resonant (PR) controller. Because a sinusoidal reference stimulus can be observed at the resonant frequency without even a steady-state error. It's because there is a big gain throughout PR controllers close the resonant frequency [20],[21]; in fact, the inverter transmission feature is accomplished by the lag caused by the production of PWM as well as the sampling [22]. Instead, the change between the grid voltage and the output voltage of the inverter is pumped into the transfer function of the grid filter, which consists of the grid current which only returns to the PR controller.

Voltage Controller. The voltage from the DC-link has been managed by a closed-loop voltage controller. Reference value of DC-link voltage can be controlled by a voltage control loop, that garble the value of the implanted grid current. PV-generated DC voltage regulates the dc-link voltage through the control loop and generates current reference for inserted grid current. The DC voltage regulator is normally regulated with the PI controller. The diagram for the voltage regulation is shown in fig.8.

Grid Synchronization. An effective grid control mechanism, and a robust synchronized system is shown in fig.9. are predominant in Grid-integrated PV system implementations [20]. Grid information like grid voltage as well as its phase angle are criteria that the controller needs. PLL-based approaches are popular along with many other strategies of synchronisation [21].

Fig.9. Overview of the grid synchronization and VAR controller.

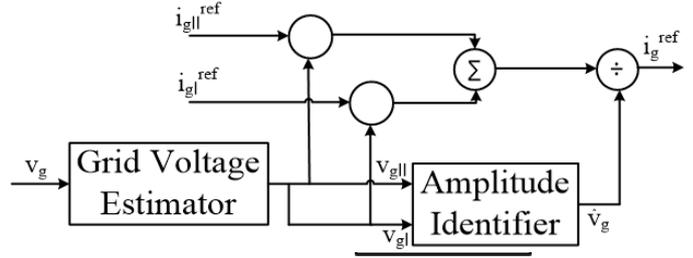


Fig.10. Block representation of Phase Locked Loop

Some of the conventional grid synchronization techniques is to replicate grid voltage in such a way in which the phase of the grid voltage reference and output current remains same. The method can be clear but perhaps the distortion and transient irregularities are distributed from the grid output, which would be undesirable in grid-connected implementations. Often, the solution declines to get any control of reactive power for the inverter. Then, PLL is also commonly used by the Grid-connected Photovoltaic system systems

The inverter utilizes the quadratic form of input to sync up the grid over PLL. Multivariable filter takes care of the voltage harmonics caused by the imbalances and distortion. PLL is a d-q reference frame grid voltage detection that moves calculated voltage to orthogonal terms, dividing d-q voltage to secure the grid phase. Orthogonally divided d-q voltage is generated by d-q reference frame when the grid phase is locking with three-phase voltage. Two of PLL's main components are phase detector and loop filter, as shown in Fig.10.

III. SIMULATION ANALYSIS AND RESULTS

From Fig.2, Simulation of the suggested RPI control technique was performed to show the effectiveness. Device specifications are specified in table 1.

TABLE 1. SIMULATION PARAMETERS REQUIRED

| | |
|----------------------------|--|
| PV array | Pmax= 3500W, 1 string, 14 series connected module, Voc= 37.6V, Isc= 8.55A (per module) |
| Normal Grid Amplitude | Vgrid= 239.1(RMS), Igrid= 14.34(RMS) |
| Normal Grid Frequency | f= 50Hz |
| LCL-Filter | L1=4.366mH, L2=4.366mH, C= 29.42μF |
| Sample Times | Control system=26.45μs, PWM generator= 1.322μs |
| DC Voltage | Vdc= 432V |
| Parasitic capacitance | Cp= 4nF |
| Filter damping resistor Rd | Rd= 32.92mΩ |

In simulations a PR current controller including harmonic compensation packages has been introduced for preserve an adequate efficiency of the power. Also, with power controller, the αβ-frame is integrated. A distribution system consisting of a grid-connected PV system which uses the MATLAB / Simulink interface to assess the efficiency of the proposed techniques.

A. Normal operating condition

The grid-connected Photovoltaic unit works in MPPT mode, subject to normal grid conditions, to supply quite enough power as feasible to the grid and to attain close to 1 power factor. A very prominent simulation results are described under Fig.11, 12, 13, 14. Those calculations was carried out at temperature (25 ° C) and constant irradiance (1000W / m2). They're chosen to highlight specific points of system behaviour. The reference and measurement waveforms are shown in Fig.11, 12, 13, 14. These figures shows a few of the Photovoltaic system characteristics that are given during normal conditions. Fig.11 displays the photovoltaic generators' maximum PV output and the active and reactive

output pumped into grid. Active power is regulated via the inverter at a steady-state, and the reactive power is forcibly turned 0. The reactive power rotates on its reference indicating the high efficiency of grid current controller and the role of the unity power factor.

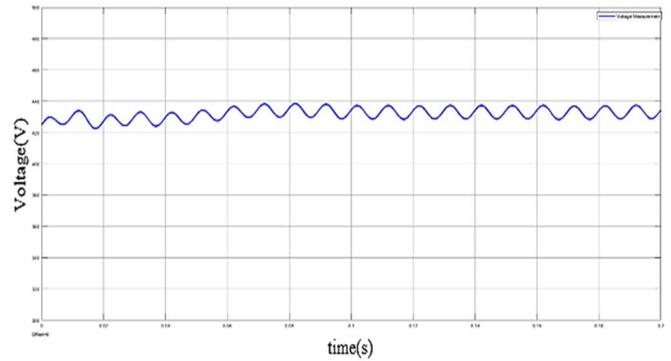


Fig.12. System result; dc-link voltage (measure).

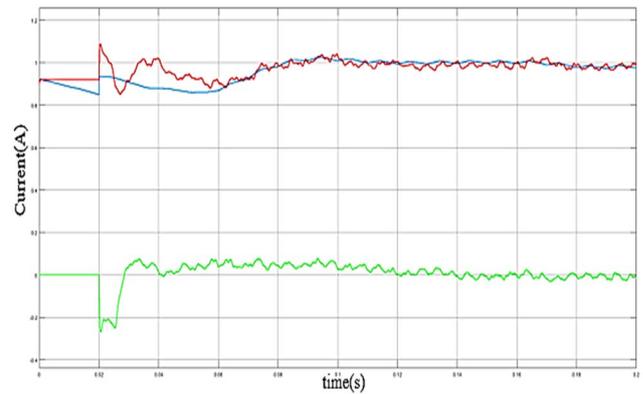


Fig.13. System result; Inverter current d(red) and q(green)-component (reference and measure).

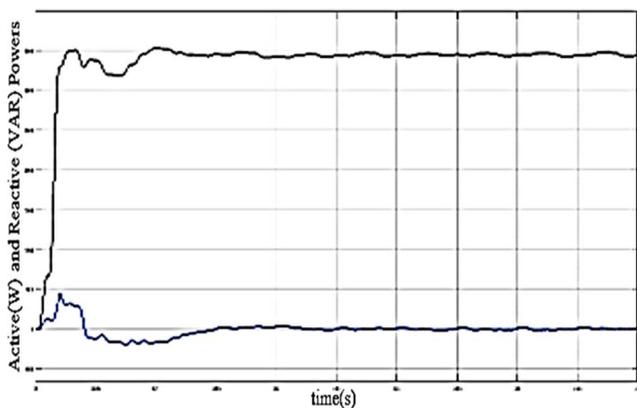


Fig.11. System result under 1000W/m² and 25°C; Inverter output active (black) and reactive (blue) powers.

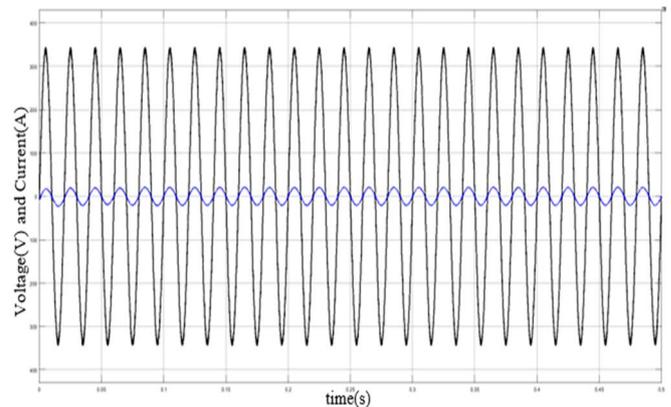


Fig.14. System result; Current(blue) and Grid voltage(black)

The inverter's active power rotates about its peak Value. One can see that the power output of inverter matches their reference in normal operation, and also that it provides average power control. Maximum photovoltaic power is roughly equivalent to the output power of the inverter, since the losses of the converter are ignored. Maintained at a steady

level, the dc-link voltage quickly followed its reference voltage at deadbeat (V_{dc}^*) can be seen in Fig.12. Consequently, active power produced by Photovoltaic Generators has fully incorporated into the grid. On inverter hand their comparisons were accompanied by the d-components in current and grid voltage and configuration shown in Figs.13 and 14. Under normal conditions in grid, such outcomes appreciate the overall performance of the different control loops.

B. Grid fault operation mode

Unit inserts reactive power required to sustain the voltage through LVRT operation and also handles the active power. A voltage sag is implemented at the PCC to test the actions, in Fault Operation Mode, of proposed control scheme. The grid-connected Photovoltaic system result is demonstrated in Figs. 15, 16, 17 and 18 below the 30% -500ms voltage sag. The voltage sag has a span of 0.5s to 1s for 0.5s. On the side of PV converter, maximum PV voltage, PV current and PV power are exactly same. As shown in the Figs. 15 and 16, such variables stay basically their references. The voltage sag has no impact on the maximum power.

failure. It is about preserving equilibrium power between grid and photovoltaic generators. There is a lead / lag in phase among voltage and grid side line current, as may be noted in the figure. It is necessary to monitor a limited dislocation between the synthesis current and voltage on line, the current efficiently inserted into grid. Consequently, the unity power factor isn't really reached during the grid voltage drops and the inverter, for sure, will have a reactive power.

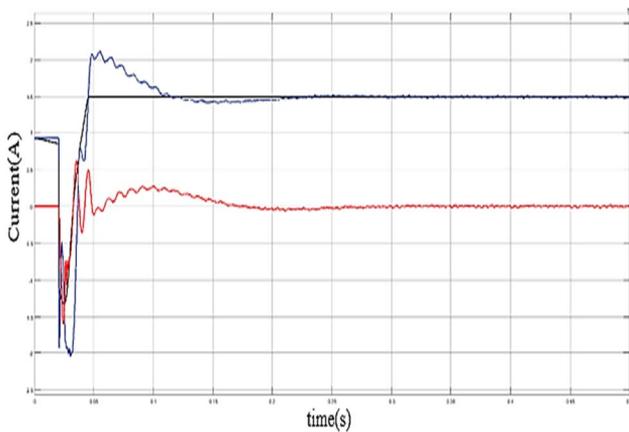


Fig.15. System result under 30%-500ms voltage sag: inverter current d(blue) and q(red)-component (reference and measure).

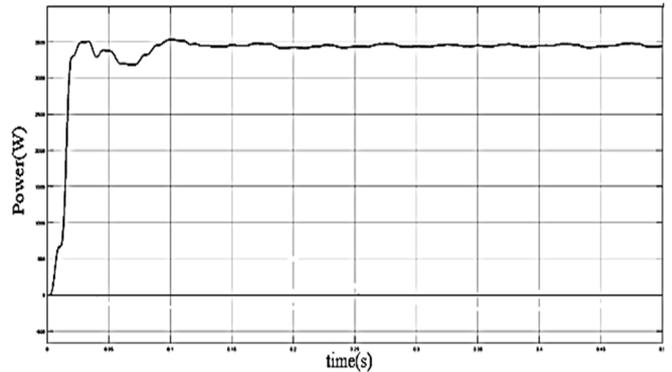


Fig.16. System result under 30%-500ms voltage sag: PV power (measure).

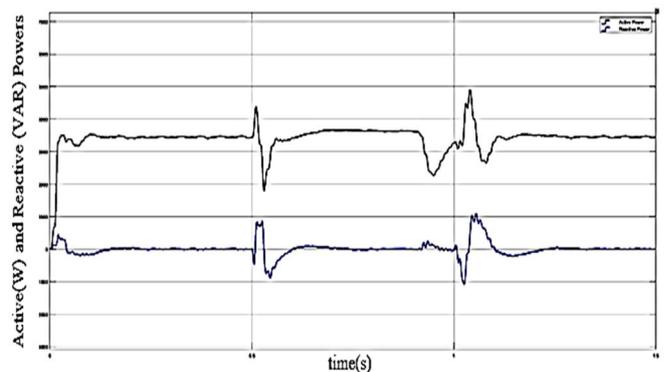


Fig.17. System result under 30%-500ms voltage sag: inverter output reactive (blue) and active (black) powers.

The effect of the voltage sag occurs only on the grid side, as indicated by Fig.17. The averages for reactive and active power detract by respective actual values. Inverter pumped mean active power will drop to 3.4 kW whereas the reactive power will rise to 226VAR to overcome the voltage drop. When-grid voltage is drop to 70 percent (nearly 166V) at PCC, output current of inverter rises as for fault and approaches to optimum inverter current. Thus, the inverter's output power is relatively low than the Photovoltaic generators inserted maximum power. So, the distinction among these powers was kept in capacitor of dc-link. DC-link voltage (V_{dc}) thus goes up to a greater level that can affect the capacitor. After removal of the fault, the active power of the inverter output rises and attains maximum value of PV power. Simultaneously, dc-link voltage drops and touches its reference point, slowly dispersing the power into the grid.

Fig.18 Displays output current of inverter and the grid voltage at PCC. Waveform of the voltage decreases, and amplitude of the inverter current gets rise at the time of

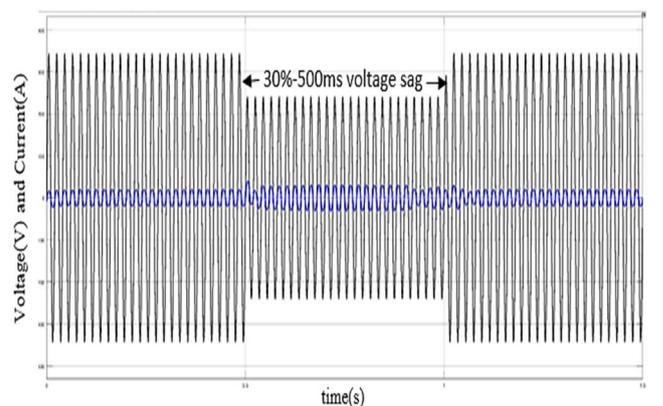


Fig.18. System result under 30%-500ms voltage sag; inverter output current (blue) and grid voltage.

IV. CONCLUSION

A control scheme was built in this paper across a dual-stage grid connected Photovoltaic system that operates during normal condition and with consistent drops in grid voltage. Its tag to upgrade the reliability throughout maintenance of grid failure and to help stop serious accidents. The simulation can verify the effectiveness of the symmetrical voltage drop along the way. The command recommended in normal operating mode increases the Photovoltaic power to maximum power as well as keeps the voltage for DC link stable. At same time, at unit power factor, it injects photovoltaic energy into grid as well as a low harmonic distortion current. In the fault operating mode, the controlling method inserts the required quantity of reactive and active power into grid. Therefore, it was also found that proposed control strategy has high performance in both the transition phase and the permanent phase in various modes of operation. It successfully solved the problem of high DC bus voltage, improved the stability of the whole system and increased the connection time in case of network failure. It also has driving capabilities and helps improve the reliability of the system. In future research, the proposal will be compared to other methods which aim not to generate photovoltaic energy during grid failures.

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