International Journal of Engineering Works
ISSN-p: 2521-2419
ISSN-e: 2409-2770
Vol. 6, Issue 12, PP. 459-465, December 2019
https://www.ijew.io/
https://doi.org/10.34259/ijew.19.612459465

Improvement of Dynamic Performance using the Grid-Tied Photovoltaic (PV) System with Nonlinear Controller

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Received: 07 November, Revised: 18 Novemeber, Accepted: 21 November

Abstract— Grid connected Photovoltaic (PV) system installations are rapidly growing around the globe to meet the increasing demand of electricity, this results in a high penetration to the electrical grid. A great deal of effort should be made to ensure the functionality of the PV system at the optimal level. Due to its non-linear nature, PV system can't handle electrical faults, which may lead to voltage sag at DC side while simultaneously generating dynamics at AC side. This work offers techniques for improving the dynamic performance of the PV system by controlling voltage sag through the application of fuzzy logic (FLC) based maximum power point techniques (MPPT) at DC-DC boost converter and the regulation of dynamics at inverter by using positive and negative sequence current controlling techniques at the time of grid faults. In the event a fault occurs, fuzzy logic based MPPT controller will be activated, instead of the simple MPPT techniques to maintain constant DC voltages. Such methods are applied by designing a MATLAB / SIMULINK 1-MW PV system and validating the tests by adding faults in the system.

Keywords— Fuzzy logic based MPPT, positive and negative current controlling techniques, voltage sag, boost converter, point of common coupling.

I. Introduction

In the domain of electricity generation, the share of renewable energy and that of grid connected PV system are increasing day by day, and as a result, winning major part in fulfilling the growing electricity demand. Some new complications seem to have arisen in grid connected PV systems, which must be encountered for secure and reliable system operation. The PV panel has an optimum operational point at which maximum power can be delivered to the load by PV panel [9]. Such operating point is generally called the maximum power point (MPP). Due to the non-linearity of the voltage-current behavior of the solar panel, the maximum operating voltage due to variance in response to variation in solar irradiance and cell temperature is difficult to assess accurately. Maximum power point (MPP) monitoring shall be carried out to recognize the maximum power point of operation; the solar panel shall be adjusted accordingly to operate at that operating voltage for the acquisition of maximum power. The PV system efficiency can be improved by extracting maximum power from the PV module while adjusting the voltage of the PV module. The MPPT controller is therefore expected to control the new adjusted maximum power point (MPP) if temperature and/or irradiance changes occur. Most monitoring methods for MPPT have been developed for this function in the last years [15-16]. Photovoltaic (PV) panel has an optimum voltage where it can produce maximum power at that particular point. As PV modules have non-linear characteristic due to changes in temperature and solar irradiance, it is difficult to determine the point where maximum power can be extracted [7]. Genetic algorithms-based optimized fuzzy logic controller has been used for maximum power-point-tracking in PV system and compared with perturbation and observation techniques, showing better performance [8]. Fuzzy logic-based MPPT has been designed to improve the performance of the PV system. It has been examined under varied irradiances at different temperatures and has been observed to produce more stable power as compared to common MPPT techniques. Hard effort should be made to operate PV system optimally [12] due to which different techniques and methodologies have been suggested for extracting maximum power from the PV modules, with each technique having its own pros and cons and limitations. During the grid fault, the main goal is to keep the DC voltages of boost converter constant at the inverter. In this work, fuzzy logic based MPPT control scheme is presented to adjust the duty cycle and produce regulated DC voltages. Fuzzy design is simple and as such, does not require knowledge of the precise model. The aim of fuzzy is to assist the MPPT to minimalize voltage variations during grid fault. By gaining information about the variation of power Δp and the variation of power due to variation in voltages $\Delta p/\Delta v$, the fuzzy can control the appropriate magnitude of the perturbed voltages to P&O MPPT for more iterations. P&O MPPT [14] will decide, and accordingly place an increment or decrement of voltage to the existing PV operational voltage and will continue to provide pathway to the MPP. There are components of positive and negative sequence during grid fault, resulting in ripples twice the grid frequency if proper control schemes are not introduced for controlling the negative and positive sequence of the grid current; as a result, the AC power vaccinated to the grid will not be constant. This will in turn result in ripples in the DC bus voltage, which may produce some serious issues for the grid connected PV system. Several techniques are implemented for the improvement of the dynamic behavior of the PV system during grid fault; feed-forward current-control loop (FFCL) improves the dynamic performance of the PV system when the irradiance of the PV system is changing suddenly and continuously [1], resulting in fluctuations in the DC-bus voltages. FFCL turns to hasten the response of inverter current references, resulting in dynamic response improvement of the injected current. A new control strategy has been used [2], by proposing uncertainty and distribution estimator (UDE) based current controller; the DC bus voltage of DC/DC converter controller is regulated in a way so as to build the relation between the MPPT function and the power flow control. By proposing bounded voltage power flow control strategy, AC voltage regulation through UDE has been improved. Since the voltage sag period is short, the soft behavior of the controller, along with a fast-dynamic performance, is the utmost significant issue in the low voltage ride through (LVRT) duration. Recently, some techniques have been introduced, such as Proportional Resonant (PR) controllers, to control single-phase PV systems in LVRT mode [3]. However, these techniques were uncertain as to their involvement in the LVRT mode. In PR controllers, a fast-dynamic response can be achieved by tuning the gains of high bandwidth PR controllers, but typically the phase margin is reduced. The design of PR controllers, therefore, requires a trade-off between dynamic response and stability. In order to make the development of grid-connected PV systems a successful business opportunity, it is necessary to improve the cost, efficiency and life expectancy of the power digital interface [4].

Whenever there is a fault on the grid side, the DC voltages at inverter change abruptly; consequently, traditional MPPT techniques can't handle the sudden change in voltage, resulting in voltage sag [10] at the inverter and the production of harmonic at the AC side. Based on the symmetrical components, a protection scheme is implemented [11] to deal with the LVRT problem but has the failure of the high current pressure on the low grid and unbalanced voltage. The current-source-inverter (CSI) provides benefits over voltage-source-inverter (VSI) in terms of intrinsic boosting and short-circuit protection capability, direct current output regulation and simplified ac-side filter design. Distributed generation (DG) systems are usually based on power electronic converters that produce harmonics, and by using passive filtering switching harmonics need to be minimized by using LCL filter [5-13]. Model-Predictive Control (MPC) for single-phase PV inverters has been proposed for the LVRT operation. Proportional-integral controller designed using Whale-Optimization-Algorithm (WOA) techniques has been used to control DC chopper and grid inverter for achieving maximum power point and improving dynamic voltage performance of the Photo-voltaic system [6]. Based on the aforementioned discussion, no controlling techniques have been applied for constant DC link voltages and stability of the system during unbalanced condition. Some of the challenges, which have not been addressed here, shall be dealt with in the coming paragraphs.

This focus of this paper is on controlling DC link voltages and maintaining system stability by applying a negative and positive sequence current regulator to provide appropriate voltage references to the grid-connected inverter and a fuzzy logic based MPPT controller to extract maximum power in order to sustain DC link voltages at a constant level. Voltage/current loop restriction-based controller, while selecting the PI controller, was used to control positive and negative current sequences produced during the unbalanced state, keeping in mind the delay produced by the filtering technique while extracting the current and voltage sequences.

II. DESIGN OF CASE SYSTEM

The PV farm used in this paper is designed in MATLAB-SIMULINK, a three-phase (3- Ø) grid connected PV system (GCPS) with generation capacity of 1MW at standard test conditions (STC), connected to fuzzy logic based MPPT DC-DC converter. The input of 1.1 MVA inverter is connected to the output of DC-DC converter, low voltage side (415V/20KV) of 1.2 MVA transformer is connected to the output of the inverter through a filter having L=100µH/phase and R=1mΩ/phase, the magnitude of instantaneous voltage is represented by e_{abc}. Fault is introduced at low voltage (LV) side of transformer for system analysis and tests. System design is shown in Figure. 1.

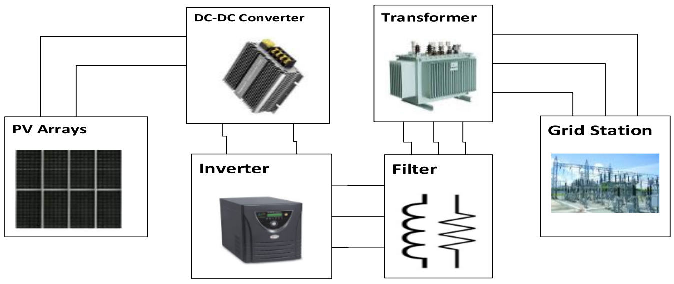


Figure 1. Design of case system

A. *Design of Fuzzy Logic Controler (FLC)*

During the occurrence of a grid fault, while sensing the change in voltages at point of common coupling a fuzzy logic controller has been designed, because, it has the capacity to deal with imprecision and uncertainty and can be used to make the most of the opportunity to design control rules. An FLC competes with human decision-making and has the capability to perform approximate data, resulting in the determination of accurate solutions. FLC is effective when mathematical modeling is difficult to implement and FLC is designed by using If/Then rules. It is used to operate a closed or controlled loop system with a range of rules. Below is the rule table for fuzzy controller:

Table 1. Fuzzy logic rules

C-E / E	N-B	N-S	Z-O	P-S	P-B
N-B	Z-O	Z-O	N-B	N-B	N-B
N-S	Z-O	Z-O	N-S	N-S	N-S
Z-O	N-S	Z-O	Z-O	Z-O	P-S
P-S	P-S	P-S	P-S	Z-O	Z-O
P-B	P-B	P-B	P-B	Z-O	Z-O

Using FLC, the regulated DC link voltages are plotted in the Figure. 2 below:

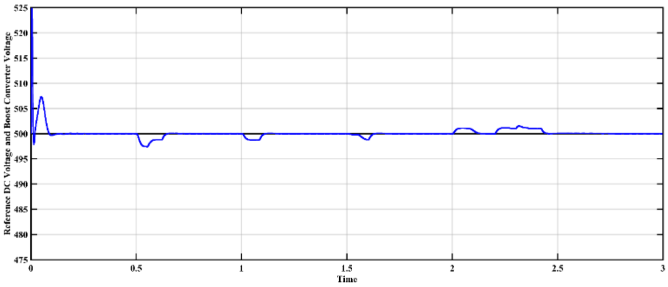


Figure 2. Reference voltages Vs regulated DC Link voltages

B. Phase Lock Loop (PLL) System

Eventually, due to the presence of low-frequency ripples in the detected voltage angle, SRF-PLL does not perform properly during the grid fault. Therefore, a more intelligent PLL should be selected to detect positive sequencing voltage during the unbalanced condition. The alternative PLL technology on the basis of moving-average filters (MAFs) has been used in this paper.

III. SYSTEM DESCRIPTION AND EQUATION

If only the positive sequence component for a grid-connected VSI is controlled, the active reference current value is obtained from the DC connection voltage and the reactive reference current is obtained through the droop control. However, the application of DC link voltage cannot be regulated by the positive sequence of active current, but also affects the negative and positive sequence of reactive and active current references when dealing with the negative and positive sequence. The instantaneous reactive and active power is given below equation (1):

$$\begin{aligned} p &= P_o + P_{c2}cos(2\omega t) + P_{s2}sin(2\omega t) \\ q &= Q_o + Q_{c2}cos(2\omega t) + Q_{s2}sin(2\omega t) \end{aligned} \qquad (1)$$

Where,

P_o represents average instantaneous value of active power
Q_o represents reactive power
P_{c2}, Q_{c2}, P_{s2} and Q_{s2} represents second order harmonics

To measure and solve the terms of power, stating relative current and voltages in a (dq) synchronous reference frame obtaining the below equations (2), shows second order hormonics.

$$\begin{aligned} P_O &= e_d^+ i_d^+ + e_q^+ i_q^+ + e_d^- i_d^- + e_q^- i_q^- \\ P_{c2} &= e_d^- i_d^+ + e_q^- i_q^+ + e_d^+ i_d^- + e_q^+ i_q^- \\ P_{s2} &= e_q^- i_d^+ - e_d^- i_q^+ - e_q^+ i_d^- + e_d^+ i_q^- \\ Q_O &= e_q^+ i_d^+ - e_d^+ i_q^+ + e_q^- i_d^- - e_d^- i_q^- \\ Q_{c2} &= e_q^- i_d^+ - e_d^- i_q^+ + e_q^+ i_d^- - e_d^+ i_q^- \\ Q_{s2} &= -e_d^- i_d^+ - e_q^- i_q^+ + e_d^+ i_d^- + e_q^+ i_q^- \end{aligned} \qquad (2)$$

On consideration of the (dq) transformation the above equation is based. The above equation can be changed into irreversible 6x4 matrix. Power ripples are produced by P_{s2} and P_{c2}. Therefore, the only terms to be controlled are the first four terms. The current reference obtained from the above equation (2) is given below as equation (3)

$$\begin{bmatrix} i_d^{+*} \\ i_q^{+*} \\ i_d^{-*} \\ i_q^{-*} \end{bmatrix} = \begin{bmatrix} e_d^+ & e_q^+ & e_d^- & e_q^- \\ e_d^- & e_q^- & e_d^+ & e_q^+ \\ e_q^- & -e_q^- & -e_q^+ & e_d^+ \\ e_q^+ & -e_d^+ & e_q^- & -e_d^- \end{bmatrix} \begin{bmatrix} P_o^* \\ P_{2c}^* \\ P_{2s}^* \\ Q_o^* \end{bmatrix} \qquad (3)$$

The main objective of the design controller is to deliver constant power during fault and voltage sag. Therefore, P_{s2} and P_{c2} should be kept to zero.

When dealing only with positive sequences, the angle extracted from the PLL can control it, but when the goal is to send constant power to the grid during the fault, both sequences should be encountered and controlled. Therefore, the current should first be calculated and then converted into a synchronous dq frame that rotates in the opposite direction and creates 100HZ ripples by communicating with each other. Filtering methods should be used to track ripples. Figure.3 denotes the extraction of current sequences and filtering techniques.

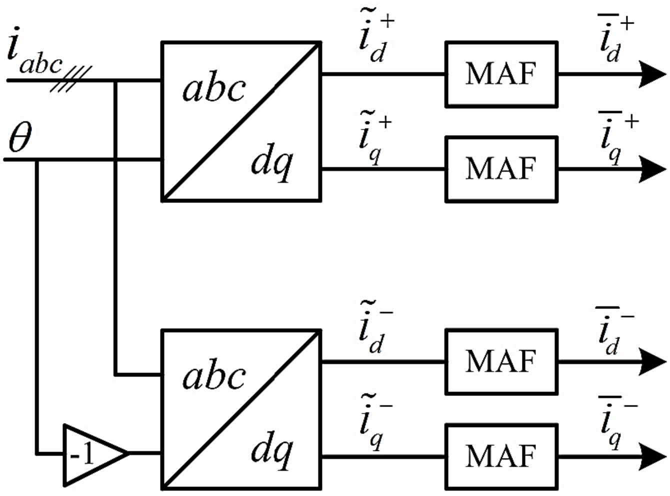


Figure. 3. Extraction of current sequences using MAF

The MAF equation (4) is as follows:

$$\bar{x}(t) = \frac{1}{Tw}\int_{t-Tw}^{t} x(t)dt \qquad (4)$$

The current control loop consists of two parallel loops, one for negative sequence control and the other for positive sequence control. There is a PI operator, decoupling terms, and dq transformed grid voltages feed forward terms in each circuit. Same technique is used for current control but with reverse direction of *w*L for negative sequence due to the reverse direction of the negative sequence rotation vector. Reference voltages will eventually be given by summing up the negative sequence and the positive sequence of voltage components to the inverter.
As shown in figure.4 i_q^{+-} and i_d^{+-} e_q^{+-} and e_d^{+-} are the positive sequence extracted currents and voltages. v_q^{+*} and v_d^{+*} are the reference positive sequence voltages. The filtered components are the grid voltage components which is used to obtain the current references. i.e., e_q^{-+}, e_d^{-+}, e_d^{--} and e_q^{--}.

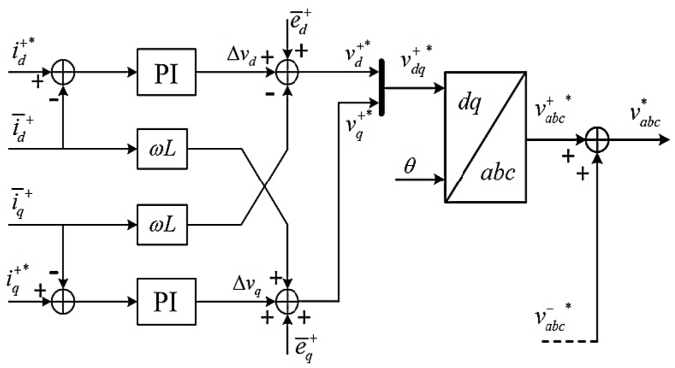


Figure. 4. Current-Control Loop (CCL)

IV. ANALYSIS OF THE SYSTEM WITH CONSTANT DC VOLTAGE SOURCE

The system's behavior and performance are evaluated firstly by keeping the dc-link constant through a dc voltage source. For steady-state analysis the power reference Q_0 is set to zero and P_0 is set to 1MW. However, during the voltage sag process Q_0 is kept 0.8 MVar and P_0 is set to zero for addressing the requirements of fault ride- through (FRT).

A. Analysis for Stability of the System

The stability of current-control-loop (CCL) is analyzed before evaluating the performance of the system during voltage sags while applying the MAFs. The MAFs introduces the delay to the current control loops which weakens the fast dynamics and may be the cause of instability.
Two independent blocks are used while considering the CCL average model for compensation of the coupling terms. The same loops are used for negative CCL.

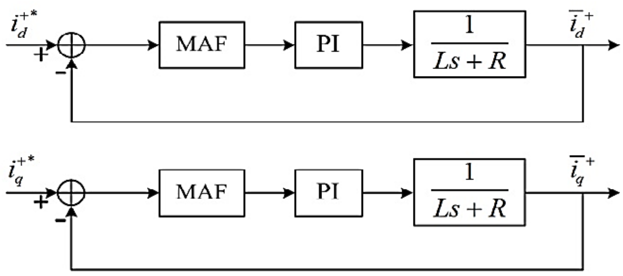


Figure. 5. Compensated average CCL for coupling terms

Converting the figure to s-domain. Equation (5) shows average model of CCL

$$\bar{X}(s) = \frac{1}{T}[1\text{-}e^{-Tw\,s}]X(s) \qquad (5)$$

To obtain the PI controller's stability region parameter, linearization of MAF is done primarily by the ' padeapproximation ' (MATLAB toolbox) process. The stable region for PI controller parameters is the small green area shown in Figure.6, considering the MAFs a 5th order approximation and filtering parameters about the other filtering procedures, i.e. a quarter (T/4) of the period of grid voltage, involving the golden and green areas in Figure. 6. Therefore, with a delay half (T/2) of the MAF is utilized in this work, the stable region is noticeably greater, lesser delays leads to have broader stable area for the parameters of the PI controllers' in the CCL.

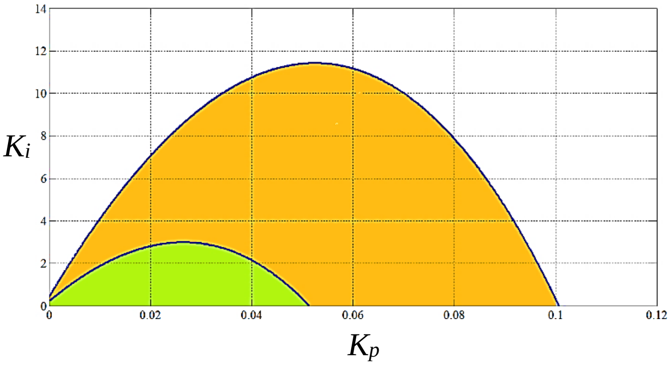


Figure. 6. Stable area for PI current controller parameters when considering MAFs in extracting the grid currents ' positive and negative sequences.

V. SIMULATIONS

Looking into the parameters defined for PI controller in Figure. 6, two regions (green and golden) defines the values for the PI parameters. The green region of Figure. 6 explains small values for the parameter of PI controller *(K_p, K_i)*. Therefore, it is known from the values that the controller's dynamic output will be slow. After some tests step responses is plotted, the values accepted for the parameters of PI *(K_p, K_i)* are (0.0015, 0.15). While using the accepted PI parameters for the test system, the fault time and steady-state response is shown in Figure. 7 and Figure. 8. Looking into figure, after fault removal and during the process of voltage sag, the dynamics are relatively slow for the PI controllers. However, the system continuous to stable in both fault and steady-state conditions. Using MAFs for filtering the grid currents has a significant impact on the dynamics of CCL. Besides, the grid voltages measured are also filtered as shown in Figure. 4, for using as feed-forward terms.

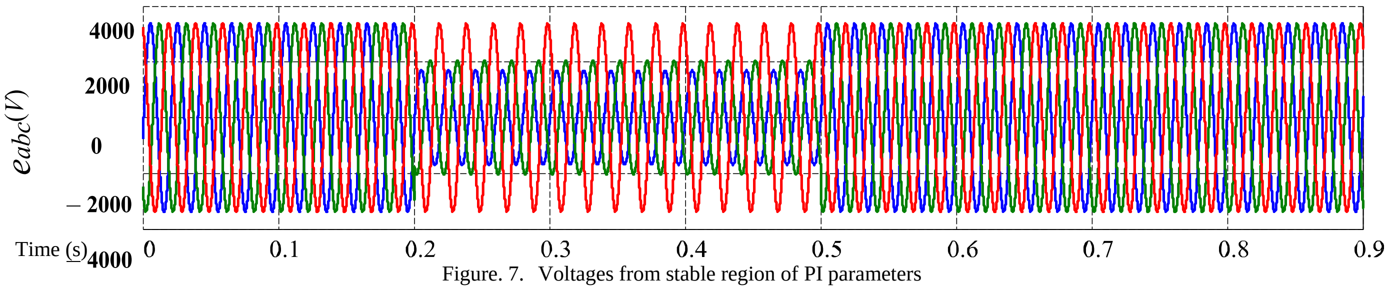


Figure. 7. Voltages from stable region of PI parameters

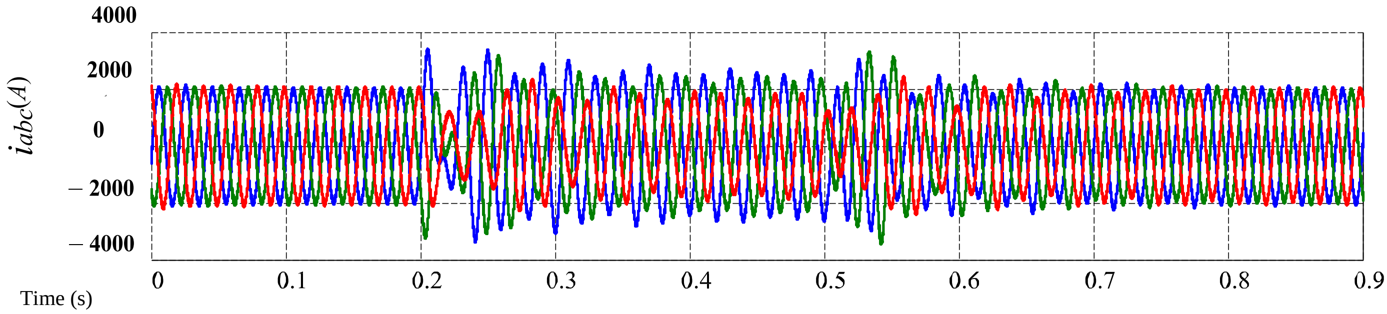


Figure. 8. Current from stable region of PI parameters

Again, the voltage filtering procedure generates some delays that weakens the system dynamic. A solution is proposed for the development of the dynamics of the current loops (CL) is to include the e_{abc} grid voltages as feed-forward terms applied after the inverter's positive and negative voltage comparisons have been summed up. The terms of the feed-forward voltage must therefore not be filtered, and the inverter voltage comparisons more easily obey the changes in the grid voltages.

The enhanced currents with the same PI controller parameters are shown in Figure. 9, and the active and reactive power generated are shown in Figure. 10. It should be noted that the system analyzation is done with a constant dc source.
However, dc-link voltages for a real PV system the should be regulated and for this purpose fuzzy logic based MPPT techniques has been used.

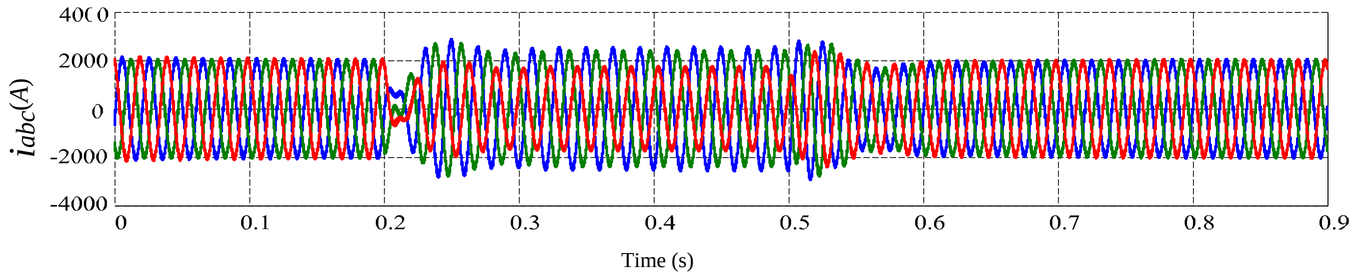


Figure. 9. Output currents improved when the grid voltage is applied as feed-forward-terms at the end of the CCL

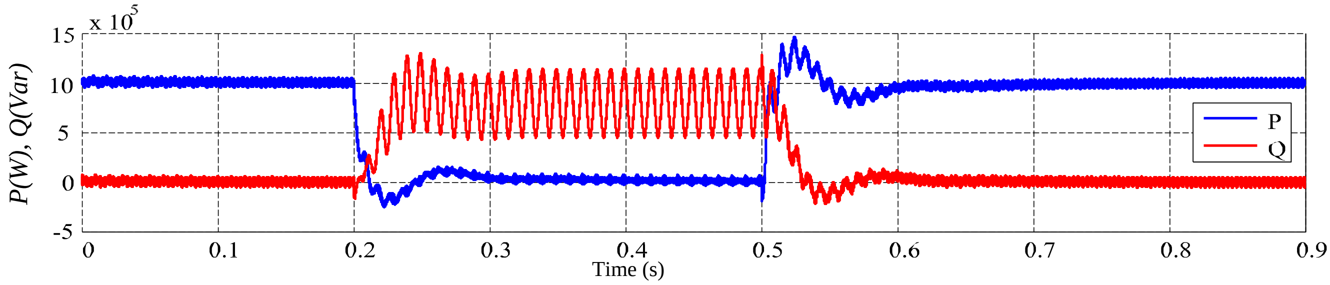
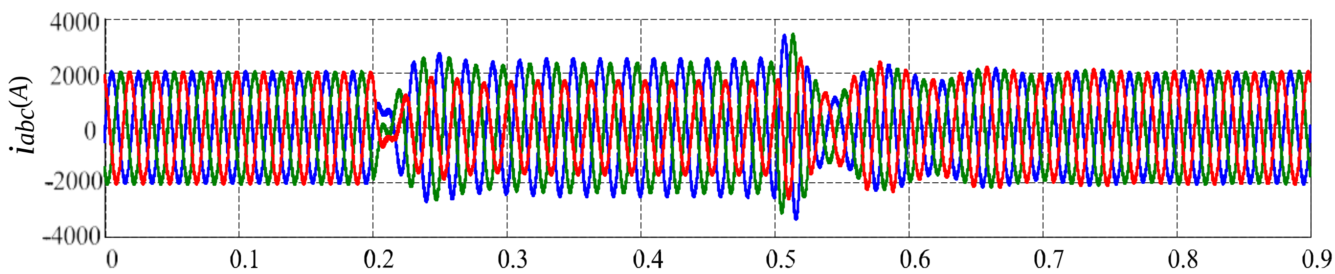


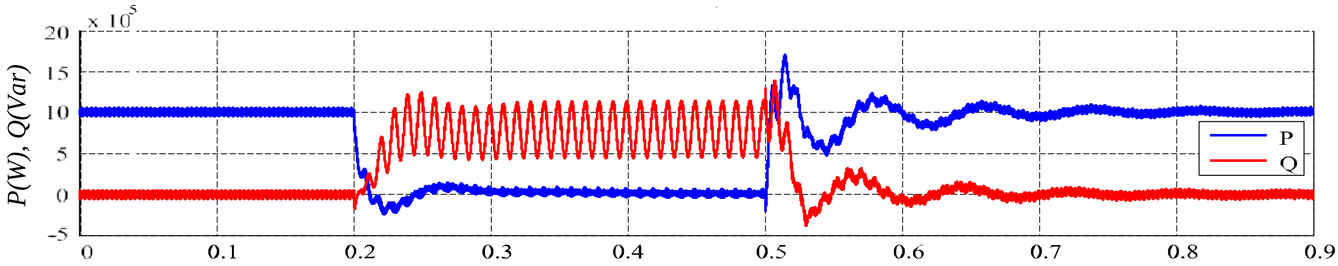
Figure. 10. Active and reactive power

A. Analysis of the Voltage Regulation with DC-Link

The system performance is evaluated in this section under regulating the dc-link voltages. The dc-link voltage is regulated at the time of the steady-state condition for obtaining P_o while it is set to zero during the voltage sag. The reactive power relationship is the same as in the previous section. However, as the aim is to provide the grid with constant power during the voltage drop there will be power fluctuations in the grid filter due to unbalanced grid currents that enable the dc-link voltage to fluctuate. A MAF is therefore used to remove these ripples for the measurement of the dc-link voltage. The system response is calculated when the dc-link voltage control loop is tested with an MAF as well as the internal current control loops. The results with the same parameters which are used in the previous section for the current control loop PI controllers with settling time t_s= 41ms and (7.65, 489) for the dc-link PI controller t_s= 78ms are shown in Figure.11. The oscillatory currents can make the inverter to disconnect due to the slow dynamics of CCL and the interaction between the MAFs and the external loop (DC link voltage loop). The CCL dynamics should be five time faster than external loop dynamics for separate analyzation. However, the structure of the external and internal loops is almost identical to that of the MAFs in the control loops. The one solution for improving the system's performance is to slow down the dynamics of the external loop; however, it will influence the dynamics of the entire system which is not really desirable. The new parameters tested for the voltage loop PI controller are (2.16, 39), which produces t_s= 176ms the settling time. The currents of the grid are shown in Figure. 12 and the active and reactive power generated are shown in Figure. 13. However, the dynamics are comparatively slow, but the system is stable.



Time (s)
Figure. 12. Waveform of the grid current



Time (s)
Figure. 13. Waveform of the active power and reactive power generated

CONCUSLION

The GCPS response is studied in this work on both positive and negative sequences under unbalanced voltage conditions. For current loops using PI controllers, it is required to implement a filtering technique for extraction of dq components from currents and voltages. All the filtering procedures, however, introduce certain delays and slow the controller dynamics. As a result, these filtering methodologies constrain the stable region parameters of the PI controller. In addition, low values must be selected for the parameters of the PI. Therefore, if the dc-link voltage is governed by an external loop, the dynamics of the controller must be relatively slow to the current control loops in order to achieve stable system performance. The overall dynamic performance is therefore substantially degraded. Using proportional-resonant controllers would be an alternative to using PI controllers. Since there would be no need for the positive and negative sequences of grid currents in the control loops, it is predicted that faster dynamics will be achieved. The future research can be done on using PR controllers.

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