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**Research Article**

# Grid Connected PV Plant with Fuzzy Logic PQ Regulator-based Grid Following Inverter

Ramesh Nenavath [1], K. Krishnaveni [2], G. Mallesham [3]
[1] *Research Scholar, Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana. Email: rameshn98@gmail.com*
[2] *Professor, Department of Electrical Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana*
[3] *Professor, Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana*

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**ABSTRACT**

Integration of PV plant into an existing grid is very complex task as the grid operates on three phase AC and the PVs generate power in DC. The PV DC power need to be maximum extracted and convert to three phase AC using a P&O MPPT based boost converter and six switch inverters respectively. In this paper the six-switch inverter is operated by a PQ based GFL control structure rather than the conventional SRF controller. The reason for using PQ based GFL controller is for attaining control over active and reactive power injection from the PV plant. In traditional SRF controller this cannot be achieved as it has no exchange of reactive power and complete active power from PV plant is injected to the grid. However, the PQ based GFL controller has conventional PI regulator for generating the reference current from the active and reactive powers comparison. This leads to under damping of the inverter creating higher oscillations, settling time, harmonics and peak overshoots in powers and voltages. In order to reduce these power quality issues the PI regulator is replaced with Fuzzy Logic regulator with high resolution. The update to the PQ based GFL controller with Fuzzy Logic regulator reduces oscillations, settling time, harmonics and peak overshoots in power and voltages. This paper includes the analysis of the proposed system with comparative graphical representations determining the better system using MATLAB software.

**Keywords:** PV (Photo Voltaic), P&O (Perturb and Observe), MPPT (Maximum Power Point Tracking), PQ (Active and Reactive), GFL (Grid Following) SRF (Synchronous Reference Frame), PI (Proportional Integral), MATLAB.

## INTRODUCTION

With the drastic increase in environmental pollution caused by the emissions from the power generation plants and transportation vehicles, the climatic disasters are increasing day by day. The livable conditions for the living things around the planet are degrading every day causing extinction of some species disturbing the eco cycle of the planet [1]. If the fossil fuel emissions are not controlled or not further reduced all the life on the planet may be destroyed. For this renewable source energy need to be adopted replacing the conventional thermal and nuclear power plants. All the electrical load including the electric vehicles need to be charged with renewable source mitigating carbon footprint [2]. Individual operation of renewable sources has less complications when compared to grid interconnection. As during standalone condition, the renewable sources need not be synchronized to other source which makes it less complex. But when the renewable source needs to be sharing its power to the grid, synchronization is mandatory [3]. Without synchronization heavy harmonics, voltages fluctuations, sags and swells can be occurred leading to damage to the devices connected to the system.

The most promising renewable sources in today technological advancements are Wind farms and PV plants. The Wind farms are huge vertical structure sources with heavy machinery and equipment deployed in locations far away from human interaction. This causes high installation cost transmission loss and risk of damage to the structures due to high winds. Whereas the PV plant is considered to be simple with only PV panels placed in the ground or the roof

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top [4]. These panels can be placed anywhere either in distant locations or even in urban areas. The PV power from the panels need to be injected to the grid using different power electronics circuits. The power from the PV panels is maximum extracted by the boost converter which is operated by the P&O MPPT technique.

Along with maximum power extraction the voltage of the PV array is boosted to higher level for sharing it to grid and also for local consumption through three phase inverter [5]. The six switch three phase inverter need to be operated in synchronization to the grid voltages. This can be achieved by SRF controller which generates pulses to the inverter for injection of power to the grid. The conventional SRF controller does not allow reactive power exchange and no control over active power injection [6]. With no reactive power support, the reactive power demand completely need to be compensated by the grid leading the drop in power factor of the source. The complete active power from the PV plant will be injected to the grid irrespective of the demand. This may lead to overcompensation and result in voltage swell damaging the devices connected to the system [7]. Therefore, the conventional SRF controller need to be replaced with PQ based GFL controller for active and reactive power control. The complete structure of the proposed system with PV plant connected to the three-phase grid through inverter is presented in figure 1.

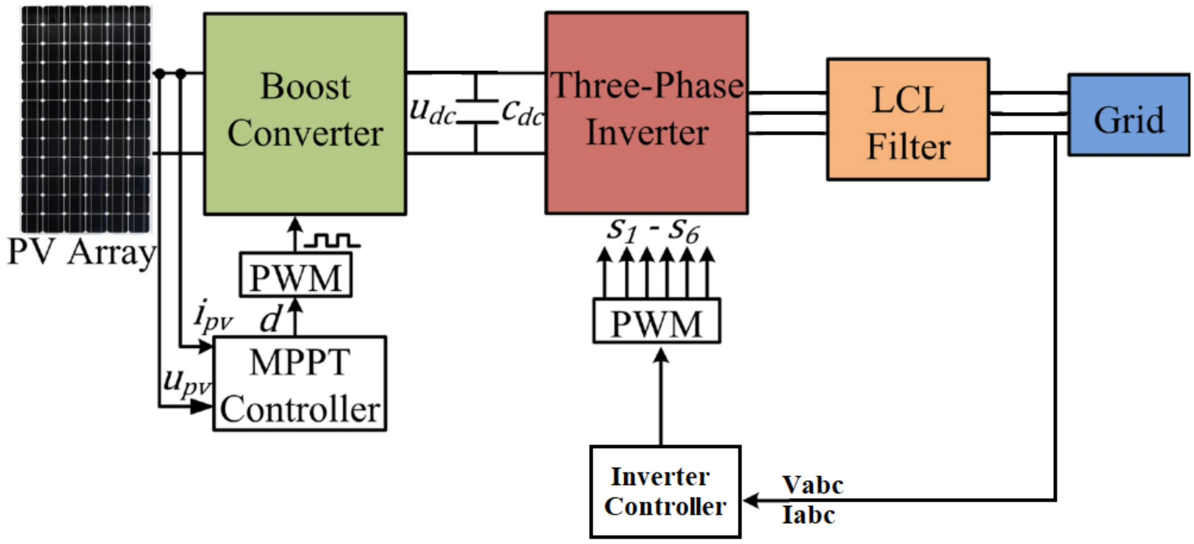


**Figure 1.** Grid connected PV plant

In the given figure 1 it is observed that the Boost converter is controlled by MPPT controller with duty ratio generation by feedback from $u_{pv}$ and $i_{pv}$ (PV plant voltage and current). The three-phase inverter is controlled by inverter controller with feedback from intersection voltages and currents (Vabc and Iabc) [8]. The reference signal for the PWM generation of the inverter is controlled by the Inverter controller. The introduced inverter controller has PQ based GFL module which controls the injected active and reactive by inverter. The traditional PQ based GFL controller has PI regulators for generating dq current reference components for the reference signal generation [9]. Due to the under damping of the PI regulators the peak overshoots, settling time and oscillations in the system are increased. This leads to uncertainties in the control modules which creates harmonics and voltages sags in the system [10]. The PI regulators are replaced with Fuzzy Logic regulators for faster response leading to reduced peak overshoots, faster settling times, reduction of harmonics and oscillations. The Fuzzy Logic regulator has 49 rule base which are defined by seven membership functions (MFs) in each variable.

This paper is arranged with introduction of the proposed modules of the system in section 1. In section 2 the configuration of the proposed system and the internal structure of the modules is presented. Followed by section 3 with Fuzzy Logic regulator design for the PQ regulator and rule base of the module. The section 4 is the result analysis of the system done using MATLAB Simulink software where comparisons of parameters like active and reactive powers, harmonics and DC link voltage are presented. The final section 5 has conclusion to the paper presenting the validation of better regulator from the comparative analysis. The references cited in this paper are placed after the conclusion.

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## SYSTEM CONFIGURATION

As previously mentioned in section 1 the proposed grid interconnection PV plant is operated with PQ based GFL inverter. The PV plant generally has two stages which include power extraction voltage boosting stage and inverting stage. The power extraction voltage boosting stage involves a boost converter controlled by MPPT controller [11]. The MPPT controller takes feedback from the clustered PV panels and controls the duty ratio of the boost converter switch. After the maximum power extraction and voltage boosting, the inverter stage involves six IGBT switches two level inverter. This inverter converts the boosted DC voltage from the boost converter to two level three phase AC which is filtered through LC filter. After the filter a step up injection transformer is connected between the PV plant and the three phase grid for power sharing. The complete structure of the two stage PV plant with grid inter connection is presented in figure 2.

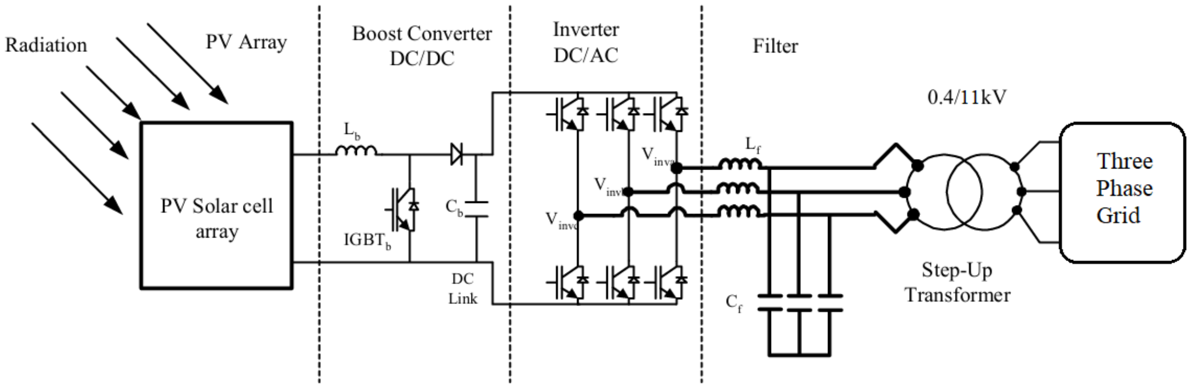


**Figure 2.** Structure of two stage PV plant with grid inter connection

As presented in the above figure the PV array generates power by the solar radiation received from the Sun. The voltage and current from the PV panels is unpredictable which change as per the solar radiation. As the PV panels cannot store power a unidirectional boost converter is used for the voltage boosting which is controlled by P&O MPPT technique [12]. The P&O MPPT technique receives accumulated PV panels voltage and current for controlling the duty ratio of the switch $IGBT_b$. The operating flow chart of the P&O MPPT technique is illustrated in figure 3.

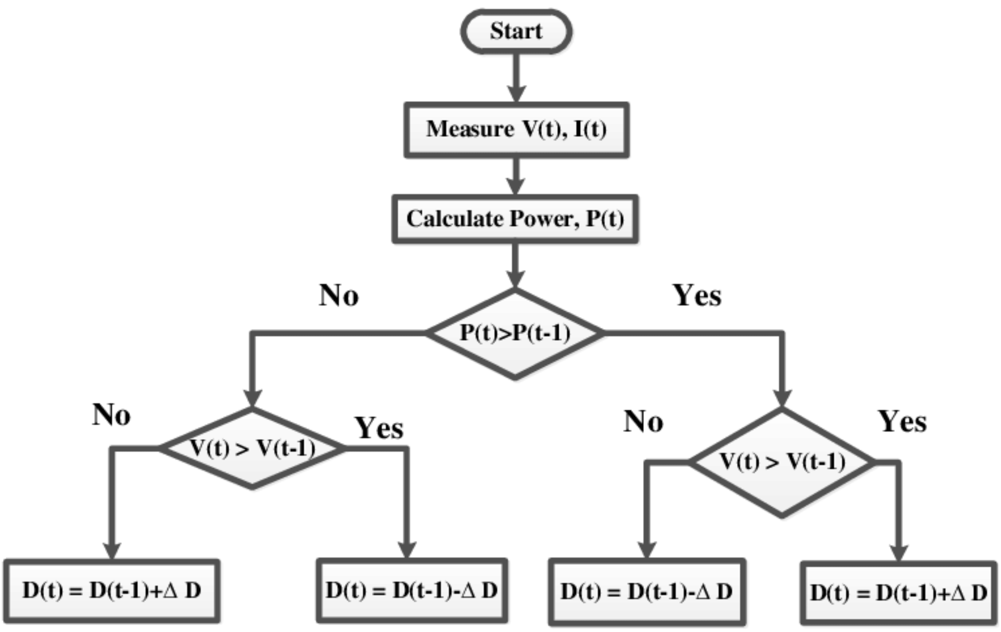


**Figure 3.** P&O MPPT technique flow diagram

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In the given figure 3, the $V(t)$ and $I(t)$ are the present values of PV panels voltage and current [13]. The P(t) is the power generated by the PV panels given as

$$P(t) = V(t) * I(t) \tag{1}$$

The past values of the voltage, current and power $(V(t-1), I(t-1), P(t-1))$ of the PV panels are generated by a unit delay block. With few relational comparisons of these past and present values of the PV panels the duty ratio of the switch is determined.

$$D(t) = D(t-1) + \Delta D \begin{Bmatrix} If\ P(t) > P(t-1)\ and\ V(t) > V(t-1) \\ If\ P(t) < P(t-1) amd\ V(t) < V(t-1) \end{Bmatrix} \tag{2}$$

$$D(t) = D(t-1) - \Delta D \begin{Bmatrix} If\ P(t) < P(t-1)\ and\ V(t) > V(t-1) \\ If\ P(t) > P(t-1) amd\ V(t) < V(t-1) \end{Bmatrix} \tag{3}$$

Here, $D(t-1)$ is the past duty ratio and $\Delta D$ is the updated to duty ratio [14]. The duty ratio from the MPPT controller is compared to a high frequency sawtooth waveform with frequency ranging from 5-10kHz, generates a pulse for the switch as presented in figure 4.

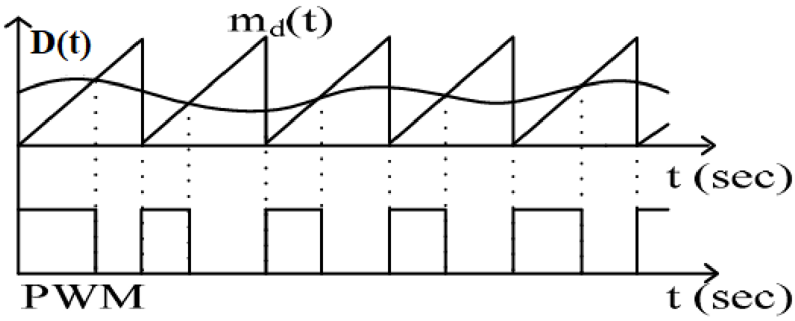


**Figure 4.** Pulse generation from MPPT technique

After the maximum power extraction and voltage boosting from the boost converter inverter stage converts the boosted DC voltage to three phase AC. The six switches of the inverter are controlled by PQ based GFL controller which is presented in figure 4.

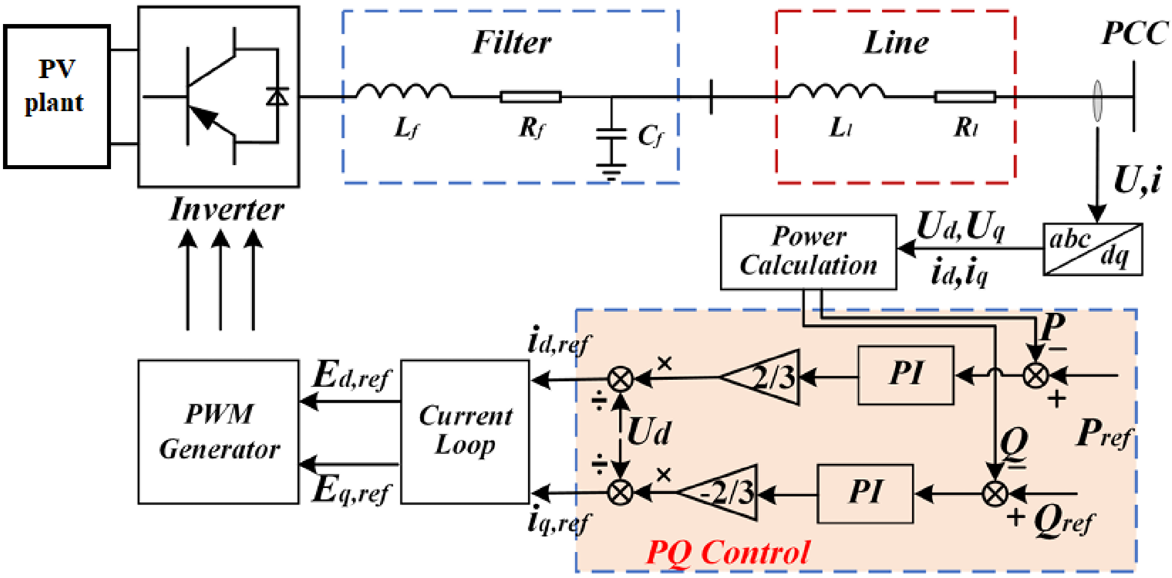


**Figure 5.** PQ based GFL controller

As per the given figure 5 the feedback of three phase voltages and currents are considered at PCC (Point of Common Coupling) [15]. From the measured voltages ($V_{abc}$) and measured currents ($I_{abc}$) the dq components are achieved using Park's transformation expressed as

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} Sin\ \theta & -Cos\ \theta & 0 \\ Cos\ \theta & Sin\ \theta & 0 \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (4)$$

In the given expression (4) the variable $f$ can be voltages or current at the PCC. The '$\theta$' variable is the angle of the grid voltage determined by PLL (Phase Locked Loop) [16]. From the dq components of the voltages and currents the active and reactive powers (PQ) are determined as per the given expressions.

$$P = \frac{3}{2}(U_d I_d + U_q I_q) \quad (5)$$

$$Q = \frac{3}{2}(U_q I_d - U_d I_q) \quad (6)$$

The calculated PQ components are compared to reference components ($P_{ref}$, $Q_{ref}$) generating active and reactive power errors. The errors are converted to required reference dq current components using PI regulators which are expressed as

$$i_{d,ref} = \frac{1}{U_d}\left(\frac{2}{3}\left(\left(P_{ref} - P\right)\left(k_p + \frac{k_i}{s}\right)\right)\right) \quad (7)$$

$$i_{q,ref} = \frac{1}{U_d}\left(-\frac{2}{3}\left(\left(Q_{ref} - Q\right)\left(k_p + \frac{k_i}{s}\right)\right)\right) \quad (8)$$

Here, $k_p$ and $k_i$ are the proportional and integral gains of the current PI regulator which are tuned as per the damping of the measured signals. There reference current signals ($i_{d,ref}$, $i_{q,ref}$) are compared to calculated dq currents (id, iq) and the error signals are fed to PI current regulators for generating reference dq voltage signals expressed as

$$E_{d,ref} = \left(i_{d,ref} - i_d\right)\left(k_{pc} + \frac{k_{ic}}{s}\right) \quad (9)$$

$$E_{q,ref} = \left(i_{q,ref} - i_q\right)\left(k_{pc} + \frac{k_{ic}}{s}\right) \quad (10)$$

In the given expression the $k_{pc}$ and $k_{ic}$ are the proportional and integral current regulator gains which are tunned as per the reference signals generated by the regulator [17]. The reference voltage components ($E_{d,ref}$, $E_{q,ref}$) are converted to Sinusoidal reference signals using inverse Park's transformation expressed as

$$\begin{bmatrix} E_a^* \\ E_b^* \\ E_c^* \end{bmatrix} = \begin{bmatrix} Sin\ \theta & Cos\ \theta \\ Sin\left(\theta - \frac{2\pi}{3}\right) & Cos\left(\theta - \frac{2\pi}{3}\right) \\ Sin\left(\theta + \frac{2\pi}{3}\right) & Cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \cdot \begin{bmatrix} E_{d,ref} \\ E_{q,ref} \end{bmatrix} \quad (11)$$

These Sinusoidal reference signals ($E_a^* E_b^* E_c^*$) are compared to high frequency triangular waveform for generation of PWM signals for the six-switch inverter. As per the reference signals the active and reactive power injection is controlled with respect to the requirement of the grid. For further enhancement of the PQ based GFL controller, the PI regulator is replaced with Fuzzy Logic module. The design of the Fuzzy Logic regulator is presented in following section.

## FUZZY LOGIC PQ REGULATOR DESIGN

The Fuzzy Logic module is an advancement to the traditional PI regulator which is critically damped with better response time and lower peak overshoots. Due to the lower oscillations in the reference signals and faster settling time the system results are enhanced with better parameters generation [18]. With more stability over the parameters the system's reliability is increased making them operate for longer time. For designing the Fuzzy Logic module the

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'Fuzzy' tool available in MATLAB software is used. The regulator is modelled with two input variables and one output variable. One of the input variable is same as the input to the PI regulator (which is error of PQ) and the other input variable is the change in error (de). The output variables of the Fuzzy Logic regulators of both the active and reactive power comparisons are $i_{d,ref}$ and $i_{q,ref}$. All these variables are included with seven MFs placed on the negative and positive side of the zero line [19]. The Fuzzy Logic variables with MFs placed in the tool can be observed in figure 6.

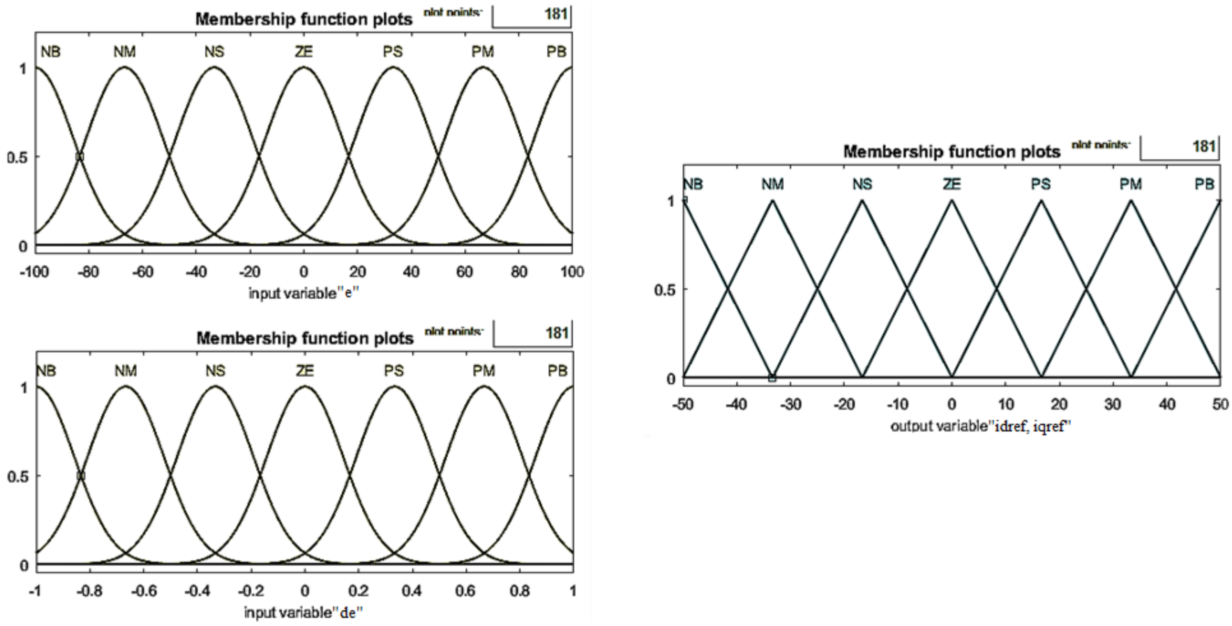


**Figure 6.** Fuzzy Logic tool input and output variables MFs

Each MF in the variables are named specifically with respect to the placement range. The extreme low and high end MFs are named as Negative Big (NB) and Position Big (PB). The medium range MFs are named as Negative Medium (NM) and Positive Medium (PM), smaller range MFs as Negative Small (NS) and Positive Smal (PS). In the center at the zero line only one MF is placed named as Zero (ZE). Each variable has the same number of MFs but different shape type [20]. The input variables are included with 'Gauss' type MFs for long range coverage and the output variable is included with 'Triangular' type MFs for accurate value generation. All these MFs are interlinked by a 49 rule table where the output is generated as per the 'IF-THEN' rule base. The IF-THEN 49 rule base for the designed Fuzzy Logic regulator is presented in table 1.

**Table 1:** IF-THEN 49 rule base

| **ece** | **NB** | **NM** | **NS** | **ZE** | **PS** | **PM** | **PB** |
|---|---|---|---|---|---|---|---|
| **PB** | Z | PS | PM | PB | PB | PB | PB |
| **PM** | NS | Z | PS | PM | PB | PB | PB |
| **PS** | NB | NS | Z | PS | PM | PB | PB |
| **ZE** | NB | NM | NS | Z | PS | PM | PB |
| **NS** | NB | NB | NM | NS | Z | PS | PM |
| **NM** | NB | NB | NB | NM | NS | Z | PS |
| **NB** | NB | NB | NB | NB | NM | NS | Z |

As per the given rule base with respect to the value placement in the MF region the output value is generated [21]. The output value is generated specific to the mentioned region accurately with faster response and reduced oscillations. Two Fuzzy Logic regulators are replacing the active and reactive power PI regulators in the PQ based

GFL controller [22] [23]. The updated system results are compared and analyzed using simulation design and analysis to determine the better system in the following section.

## RESULTS ANALYSIS

All the modules of the proposed grid interconnected PV plant with PQ based GFL inverter controller are modelled in MATLAB Simulink environment. The power electronic blocks, source, passive elements and measurement are considered from 'Electrical' subset of the Simulink library. For plotting the graphs of the data calculated after the simulation 'Scope' blocks are used for the graphical representation. Before the simulation each module is updated with the parameter presented in table 2.

**Table 2:** System parameters

| **Name of the module** | **Parameters** |
|---|---|
| PV plant | $V_{mp}$ = 30.1V, $I_{mp}$ = 8.3A, $V_{oc}$ = 37.2V,<br>$I_{sc}$ = 8.87A, $N_p$ = 200, $N_s$ = 24.<br>$P_{pv\ total}$ = 1.2MW. |
| Boost converter | $L_b$ = 5mH, $C_{in}$ = 100µF, $C_{out}$ = 12000µF. |
| MPPT | $\Delta D$=0.05, MPPT gain = 5, Dint = 0.5, fs = 5kHz. |
| Grid | 132kV, 50Hz, 2500MVA. |
| Inverter | 1.2MVA, 400V, 50Hz, fc = 2kHz.<br>Filter – Lf = 250µH, Cf = 100kVAR. |
| PQ control | PI regulator - Kp=0.023, Ki=0.005, Kpi=0.5, Kii=0.001<br>Fuzzy Logic – 'e' range = -200 to 200, 'de' range = -1 to 1 and Idqref range = -50 to 50. |

With the above parameters the simulation is updated and run for a time of 1sec in order the record the results during initial transient and steady states. All the graphs presented are comparative graphs between PI and Fuzzy Logic regulator in the PQ based GFL controller. The figure 7 shows the DC link voltage after the boost converter.

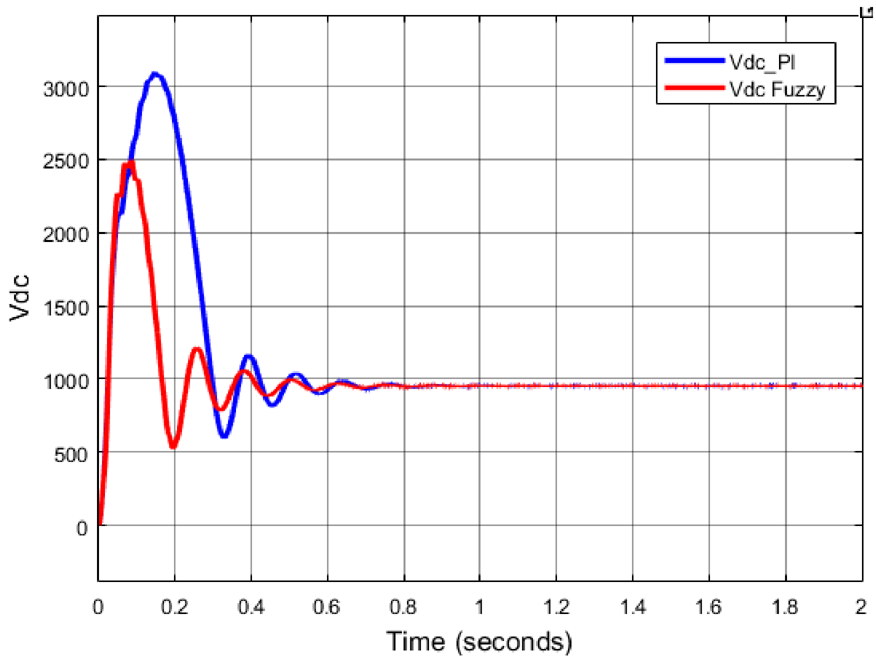


**Figure 7.** DC link voltage comparison

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As presented in figure 7 the peak overshoot of the DC link voltage is reduced from 3100V to 2500V when the PI regulator is replaced with Fuzzy Logic regulator. Along with the peak overshoot the settling time is also decreased from 0.8sec to 0.7sec because of increased damping of the reference signal. The same effect can be observed in the frequency comparison at PCC in figure 8.

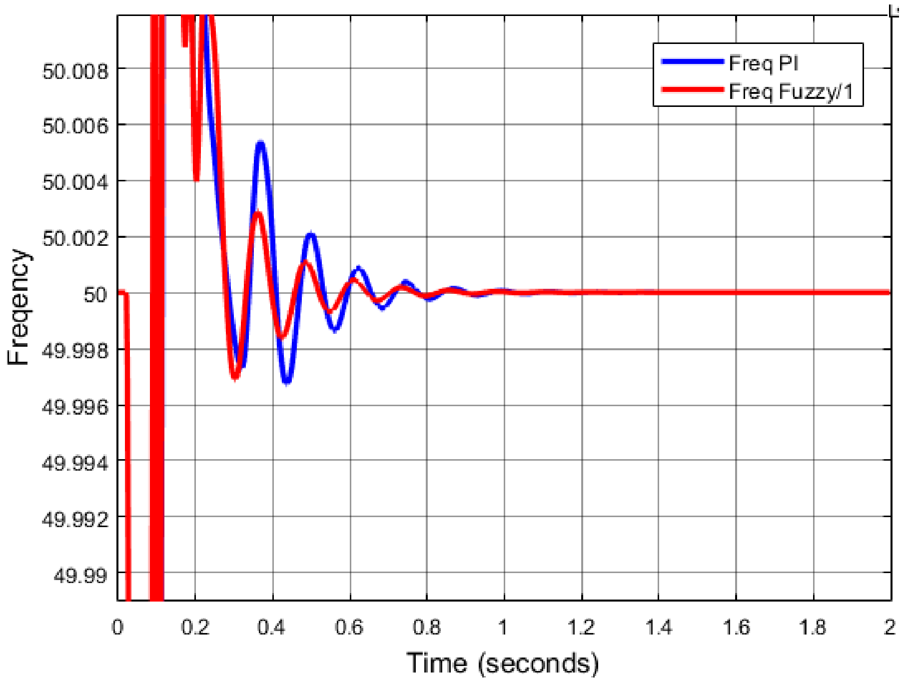


**Figure 8.** PCC frequency comparison

The damping of the controller improves the settling time of the frequency with reduced oscillations. However, in both the models the frequency is maintained at 50Hz. The three phase PCC voltages and injected currents from the PV plant is presented in figure 9.

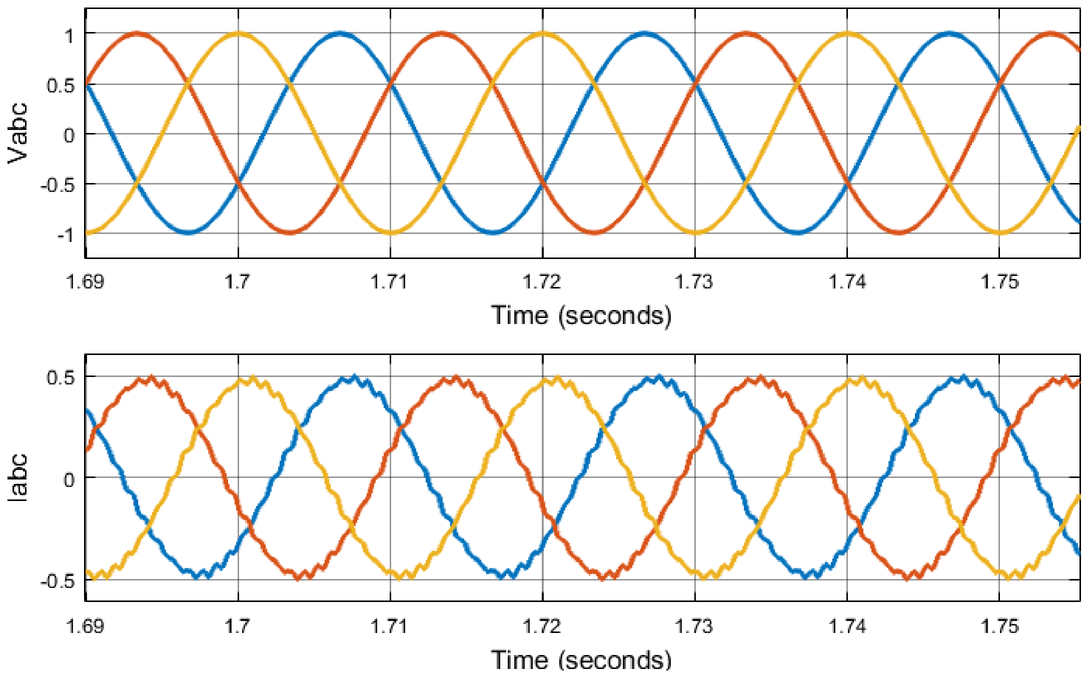


**Figure 9.** PCC voltages and injected currents

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The measurement is considered in perunit representation which denotes the nominal operating conditions with respect to the reference set in the controller. As the voltages and currents are in perunit the active and reactive powers are also plotted in perunit representation with Pref and Qref set to 0.7pu and -0.2pu respectively.

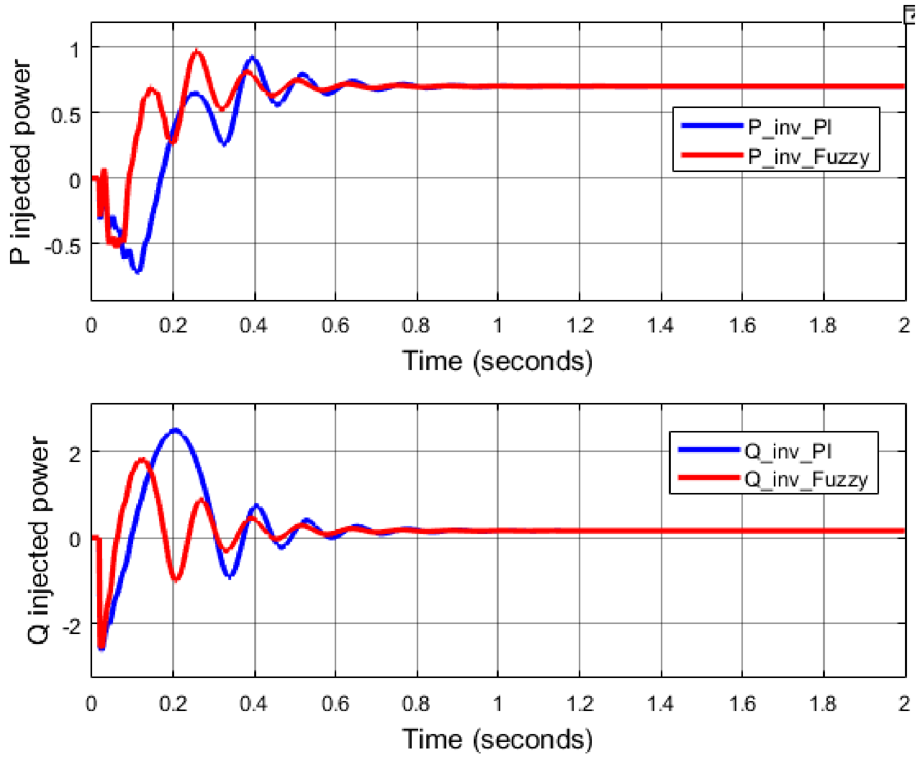
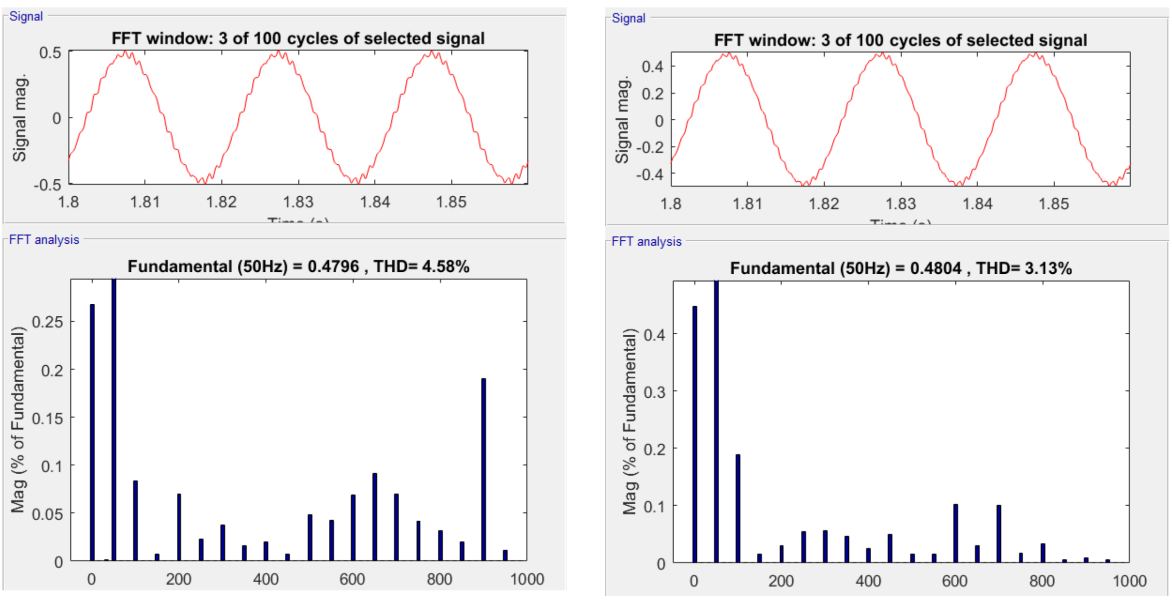



**Figure 10.** Active and reactive power comparison

The figure 10 shows the measured active power P is settling at the desired value of 0.7pu and the measured reactive power at 0.2pu which is delivered from the inverter to the grid. With the updated of Fuzzy Logic regulator the settling time and damping of the injecting P and Q are improved with lower oscillations.




**(a)** **(b)**

**Figure 11.** THD comparison of PCC current

The figure 11 represents the THDs (Total Harmonic Distortion) of the injected current when operated with PI and Fuzzy Logic regulators. It is observed that the harmonic content with the PI regulator are below 5% as per the IEEE 519-2022 standard which is further reduced to 3.13% when updated with Fuzzy Logic regulator. This is achieved due to the reduction of oscillations and better damping of the controller during initial operating conditions. A parametric comparison table with all the factors compared between PI and Fuzzy Logic regulators is presented in table 3.

**Table 3:** Parametric comparison table

| Name of the parameter | PI regulator | Fuzzy Logic regulator |
|---|---|---|
| DC voltage peak overshoot | 3100V | 2500V |
| DC voltage settling time | 0.8sec | 0.7sec |
| Frequency settling time | 0.8sec | 0.7sec |
| P settling time | 0.6sec | 0.5sec |
| Q settling time | 0.7sec | 0.6sec |
| Current THD | 4.58% | 3.13% |

## CONCLUSION

The modeling of the PV plant with maximum power extraction boost converter and grid connected inverter with PQ based GFL controller is implemented in MATLAB for analysis. The inverter is connected to the grid through filter for harmonic filtration and is controlled in synchronization to the grid. The PQ based GFL controller is used for specific control over active and reactive power injection. In order to avoid complete reactive power dependency on the grid the inverter also provides reactive power when operated with the GFL controller. However, the conventional PI regulator in the controller increases the oscillations in the reference signal resulting in increased settling times and disturbances in the system. The conventional PI regulator is replaced with Fuzzy Logic regulator for better stability over the reference signal generation. The comparative analysis presents reduction in settling time of the reference signals which lead to reduced overshoots and settling time in the voltages and power with Fuzzy Logic regulator.

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