

Designing and controlling an NPC multilevel inverter in order to connect solar cells to the grid

Mehdi Ghasemi Naveh Mahmood Abad¹, Ali Asghar Ghadimi²

*Department Electronic, Khomein Science and Research Branch, Islamic Azad University, Khomein, Iran

¹Khomein Science and Research Branch

²Assistant Professor of Electrical arak

Abstract: With the increasing use of PV cells in power system, optimal utilization of the equipment is an important issue. In these systems the MPPT controller is used to inject the maximum available power from solar energy. During day time that the active power decreases because of low intensity, the inverter is capable of injecting reactive power up to its nominal capacity and this is a chance for reactive power compensation. In this paper the aim is to propose a control method for injecting the maximum active power and if possible, the reactive power. In addition, a low pass filter is suggested to solve the problem of current fluctuations in case of unbalanced load. Simulation results on a typical system in MATLAB indicate proper performance of the presented method.

Keywords: NPC inverter, Maximum Power Point Tracking (MPPT), photovoltaic cell (PV), PI current control, space vector pulse width modulation (SVPWM).

1. Introduction

using distributed generation has been widespread recently, especially those which use renewable energies. Photovoltaic (PV) cells are used in order to convert solar energy into electrical energy. For connecting PV cells to the grid, equipment such as DC-DC converters, energy storage devices, inverters and filters must be used. So designing and controlling each equipment is of great importance.

Upcoming challenges of connecting solar generators to the grid include maximum power point tracking (MPPT), least harmonic injection to the grid and supplying local load appropriately that all can be reached by properly controlling these equipment. One of the important issues in connecting PV generators to the grid which includes local load is injection of active power equal to MPP and also injection of demanded reactive power of the load, as much as possible. In other words, correcting power factor in order to reduce the power absorbed from the grid. In this approach in addition to occupying capacity of inverter after compensating reactive power that causes fluctuation in injected power, there will be some problems in control system that increase THD [2].

In the field of connecting PV cells to the grid, different researches have been done previously. [1] Has used a bridge inverter that has high THD and switching losses because of its topological nature. Proposed method in [2] utilizes $\alpha\beta$ frame of reference and fuzzy control to determine reactive and active power respectively which has a good performance. But in case of variable loads, the control system will face trouble and injected currents will be unbalanced. Authors in [4] presented a simple control method that is easily implemented but the output current conditions high rate of harmonics and in unbalanced load condition, current balance will be disturbed severely. [6], in this method a five-level inverter is used for connecting PV that can inject high level of active power but may cause high THD if the inverter is not controlled properly. In [9] the capability of inverter to correct power factor is not used and inverter works only as an active power injector. [10], this paper does not control injected power to the grid properly and the injected power may exceed inverter power and damage the inverter.

According to the works done in this field, it can be seen that the different presented methods have problems such as high injection of harmonics and disability to correct power factor properly. Thus in this paper a control method in dq domain is used in order to resolve the above problems and inject the desired active and reactive power to the grid

regarding nominal range of system equipment. The suggested method has more advantages than previous methods; such as low THD and the output power regulation of the inverter considering nominal range for more safety.

In order to achieve the above goals, this paper is subdivided into five sections. In the second section the studied system is introduced. Active and reactive power control system is analyzed in the third section. In the fourth section the suggested control method is analyzed. The fifth section is dedicated to results of simulation and finally the sixth one is for conclusion.

2. The studied system:

The studied system in this paper that is also used in many research papers like [2] and [10] is depicted in Figure 1.

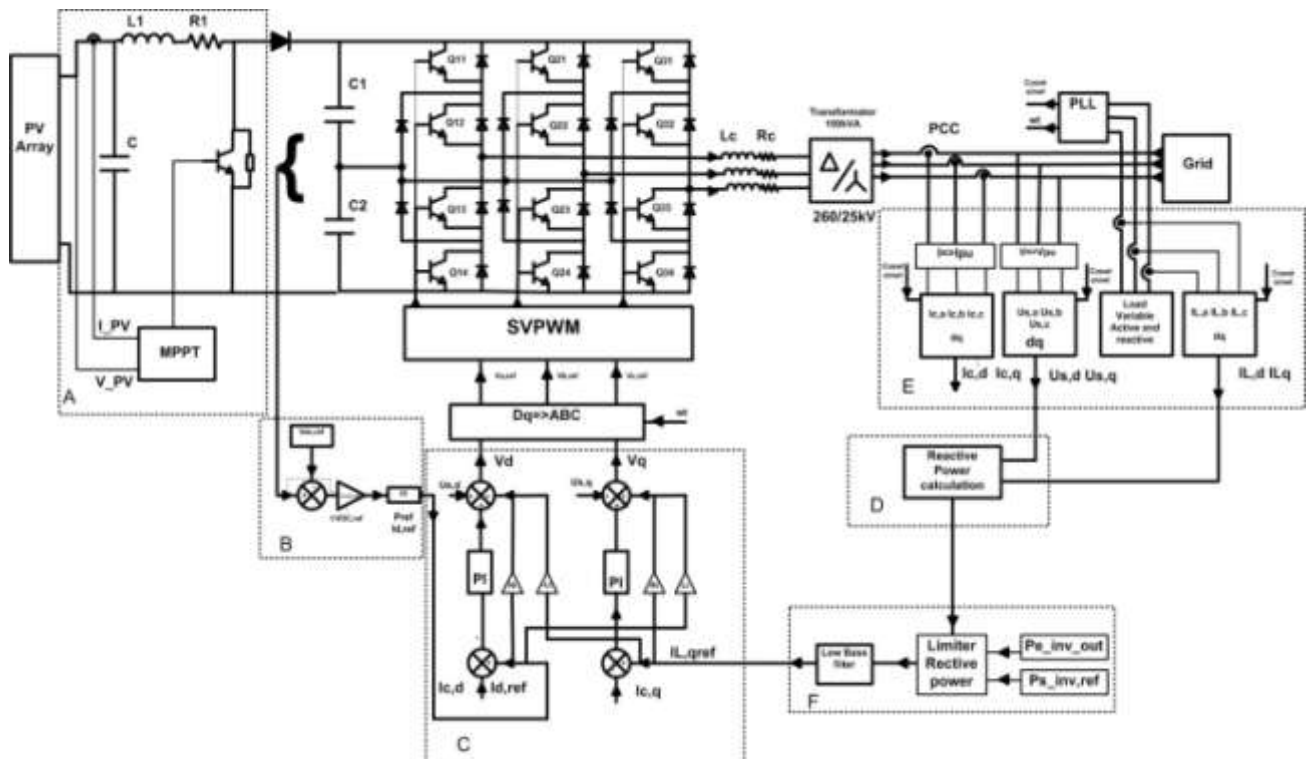


Fig 1: Studied system for injecting power to the grid and local load

The used electrical system contains the following parts:

2.1. Solar cells:

Solar cells are used as the active power source. In this paper the common model which is presented in [9] is studied and includes MPPT control circuit to gain the maximum active power. The Incremental Conductance (INC) is used for MPPT as shown in block A.

2.2. DC-DC converter:

This converter is to increase and stabilize the output voltage of PV and also to implement MPPT; mechanism and performance of this converter are available in [3].

2.3. DC bus capacitors:

Two capacitors are used for DC bus to reduce DC voltage fluctuations; the common point of these two capacitors represents the neutral point of the inverter.

2.4. NPC type multilevel inverter:

Because of its high voltage level and appropriate harmonic conditions this inverter is used for connecting high power DG to the grid. Its structure and operation are completely described in [12]. These inverters are controlled by switching methods such as sinusoidal pulse width modulation or space vector modulation, which the space vector method is of greater use because of its better harmonic characteristic and higher voltage amplitude [13].

2.5. Output filter and transformer:

This filter is to eliminate higher order remained harmonics at the output of inverter and turning the wave to a purely sinusoidal one. Design procedure for values of the filters is presented in [10].

2.6. Local load:

This load needs variable active and reactive power. It is clear that for economical reasons, PV cells must supply maximum available power. If demanded power is more than the supplied power, providing remained power is duty of network. On the contrary the excess power is absorbed by the network. In supplying reactive power the network is at higher priority. When the intensity of light is low, produced active power decrease and unused capacity of inverter can be utilized for reactive power injection.

2.7. The grid:

According to this fact that solar cells cannot supply the load in every hour of a day, there must be either an energy storage system or the grid near them. The important issue is to synchronize the inverter with the grid and this is done by PLL block [10].

3. Control system

The control system used for connecting PV system to the grid includes following parts:

3.1. DC bus voltage control system:

It is a well known fact that each solar cell has a maximum generated power related to temperature and light intensity and this maximum power should be absorbed completely for efficient use of cells. This is done by MPPT control system connected to DC-DC converter which is used after PV cells. By the way, the connected inverter to this converter must inject that maximum power of the cells to the grid and local load in order to have a fixed DC bus voltage. If the power of PV drops because of low intensity of light, DC bus voltage will begin to fall; in this situation the voltage must be stabilized by decreasing injected power using inverter. In case of increased intensity, opposite action must be taken. Block B stabilizes voltage by controlling active power and by the way, maximum active power is obtained. DC bus control mechanism is such that error of DC bus voltage ($e = V_{DC,ref} - V_{DC}$) named " Δe " enters a PI controller and the output is named $\Delta_{pref,inv}$ that forms I_{dref} which is used in control circuit.

3.2. Inverter current control: since network voltage is constant, injecting a current with proper amplitude and phase can lead to active and reactive power injection. In [10] the equation for defining v_{id} , v_{iq} which are used for inverter switching is presented as equation 1 to 4 and it is implemented in control system as block C. this block has two inputs (I_{q-ref} , I_{d-ref}) which is obtained from desired active and reactive power respectively. As stated in previous section, I_{d-ref} is calculated according to DC bus voltage loop.

$$L_t = L_{xfo} + L_{choke} \quad (1)$$

$$R_t = R_{xfo} + R_{choke} \quad (2)$$

$$Z_{base} = \frac{V_{nom_sec}^2}{P_{nom}}$$

$$R_{tot_pu} = R_{LXFO} + \frac{R_{Lchoke}}{Z_{base}}$$

$$L_{tot_pu} = L_{Xfo} + \frac{L_{choke}}{\left(\frac{Z_{base}}{2 \times P_i \times f_{nom}}\right)}$$

V_{iq} and V_{id} are calculated as below:

$$V_d = U_{S,d} + I_d \times R_t - I_q \times L_t + \frac{d}{dt}(I_d) \times L / \omega_{base}$$

$$V_q = U_{S,q} + I_q \times R_t - I_d \times L_t + \frac{d}{dt}(I_q) \times L / \omega_{base}$$

3.3. SVPWM method for a three level inverter: desired V_{id} , V_{iq} which are the output of current control block must be supplied by the inverter. So switch of inverter must be performed so that this parameters appear in output. For this purpose, after passing this signals from a dq to abc block, the switching pattern will be created. In this paper, space vector pulse width modulation (SVPWM) method is used. Basic principle of this method is described in [M.H.Rashid] it is shown in figure 2.

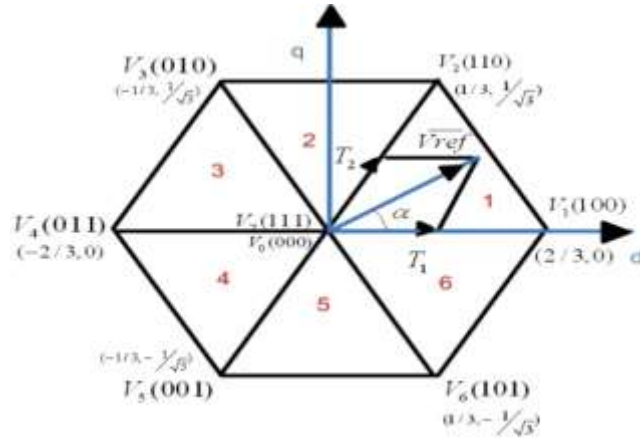


Figure 2: Space Vector Modulation

4. Suggested control method

4.1. Reactive power control procedure suggested in this paper is such that the needed reactive power of load is calculated according to its current and network voltage (block D) and then I_{q-ref} will be calculated (equation 5 to 9).

$$f_{d-q} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (5)$$

$$i_{L,d-q} = f_{d-q}(i_{L,a-b-c}) \quad (6)$$

$$u_{s,d-q} = f_{d-q}(u_{L,a-b-c}) \quad (7)$$

This I_{q-ref} with previously calculated I_{d-ref} must pass block C to form switching pattern [2].

$$q_L = \begin{bmatrix} -u_{s,\beta} & u_{s,\alpha} \end{bmatrix} \cdot \begin{bmatrix} i_{L,\alpha} \\ i_{L,\beta} \end{bmatrix} \quad (8)$$

$$q_{ref_inv} = q_L$$

For compensating reactive power of load , inverter reactive power reference must be equal to load reactive power. If the load needs reactive power, the control method has not a proper performance and inverter current start to oscillate which cause THD to be increased (this shown will simulation in next section).

Furthermore, if the rating of inverter is not considered , demanded active and reactive power from inverter may exceed from this nominal range and damage the inverter . in this paper a system is suggested as block F to overcome the above problems.

4.2 Limiter

Since the priority of inverter is to inject reactive power, therefor maximum reactive power of inverter is calculated according to power triangle (equation 10).

$$p_e^2 + p_Q^2 = p_s^2 \quad (10)$$

Normalizing equation 10 we have:

$$\frac{p_e^2 + p_Q^2}{p_s^2} = \frac{p_s^2}{p_s^2} \quad (11)$$

$$\frac{p_Q^2}{p_s^2} = \frac{p_s^2}{p_s^2} - \frac{p_e^2}{p_s^2}$$

And for reactive power we have:

$$p_{Q_pu} = \sqrt{1 - \frac{p_e^2}{p_s^2}} \quad (12)$$

According to equation (12) and block F in figure (1), we have a limiting circuit that controls current I_{q_ref} according to equation (12).

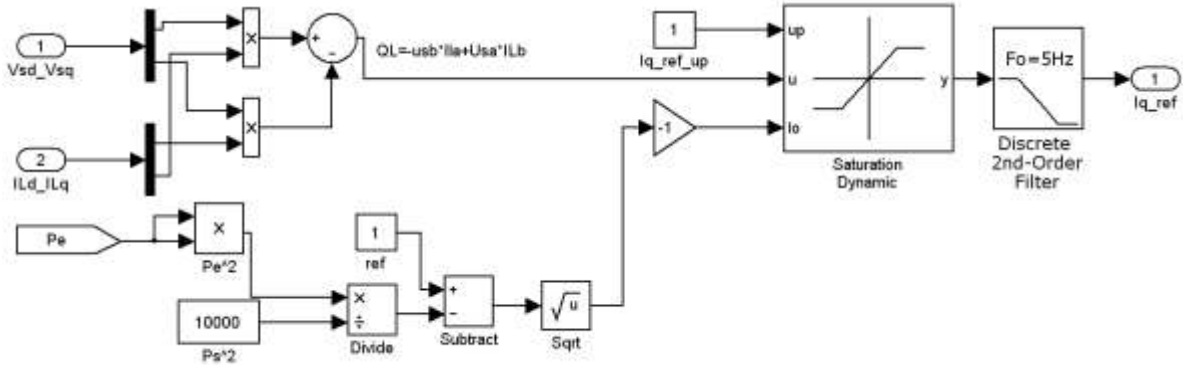


Figure 3: Reactive power control circuit regarding power of inverter with an LPF

5. Simulation

Simulation was done using MATLAB in different conditions to analyze efficiency of the suggested controlling method for the studied system. Parameters of different parts of the PV system are shown in the following table.

Parameter	value
Total transformer leakage impedance	(pu/Pnom) [RxfoLxf]= [0.002 Ω 0.06H]
Vdc	600
Us,f	260,50Hz
Fs	5kHz
C1,C2	12000uF
Lc	250uH
Rc	2mΩ
Kp	.21
Ki	20
Low bass filter_f_cut	5Hz
Pref_Kp	7
Pref_Ki	800

5.1. Analyzing inverter characteristics for no-load condition:

At first, behavior of the system is analyzed in no-load condition. At $t_0=0$ power of DG connected to the grid is 100kW because of high intensity of light. Active power of inverter (P_{inv}), grid (P_s), load (P_L) and reactive power of inverter (Q_{inv}), grid (Q_s) and load (Q_L) are shown and analyzed in Figure4. In this figure phase to phase

voltage of inverter and the grid are shown. As it is illustrated, injected power of the inverter to the grid is approximately 100 kW; and because there is no active or reactive load, all active power is injected to the grid. In this figure wattmeter shows minus one hundred kilowatts which meaning is that the grid is receiving energy from inverter. Since there is not any load, no reactive power is absorbed neither from the grid nor from inverter as it is shown. The following figure is the simulation of output voltage of the inverter and voltage of the grid in no-load condition and also the simulation of inverter when injects the whole power to the grid. It is shown that the output voltage is balanced.

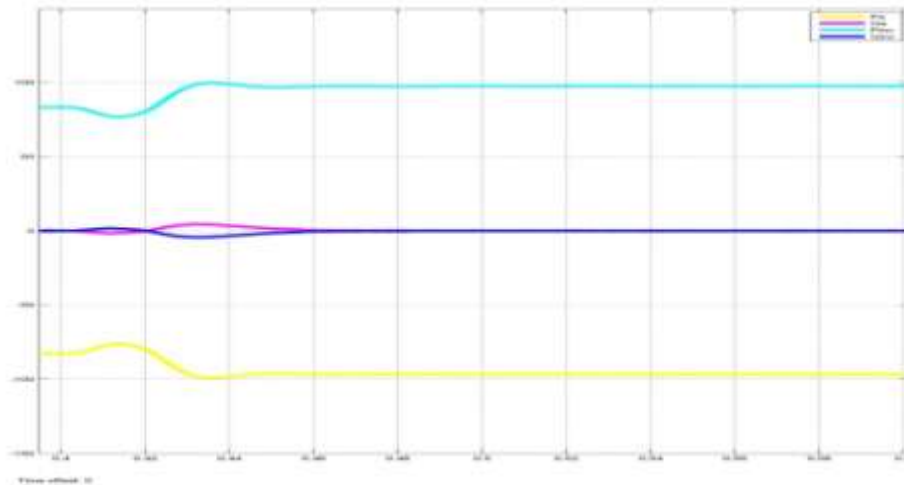


Figure 4: output active and reactive power of the inverter

According to use of inverter, switching circuit, inverter control circuit and its filter, THD of this simulation in no-load condition is better than results obtained in [2]; and it can be seen that THD=0.56.

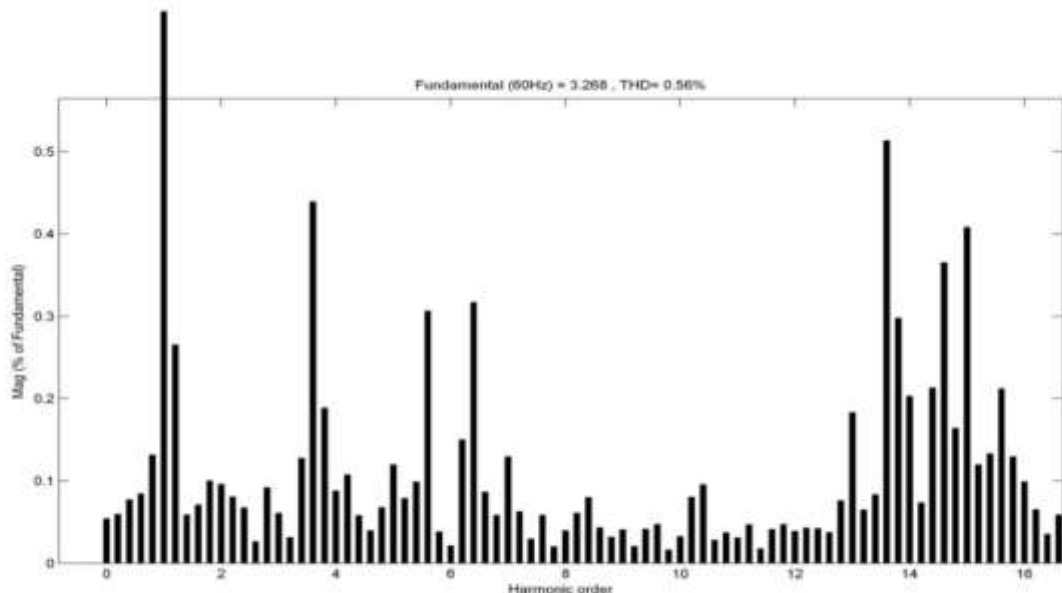


Figure 5: THD of injected current to the grid in no-load condition

5.2. Analyzing inverter characteristics in no-load condition and low intensity of light

When intensity of light is low, the capacity of inverter can be used in order to inject reactive power but since there is no reactive load, correcting power factor of the grid is not performed. Although active power has been decreased, reactive power is zero.

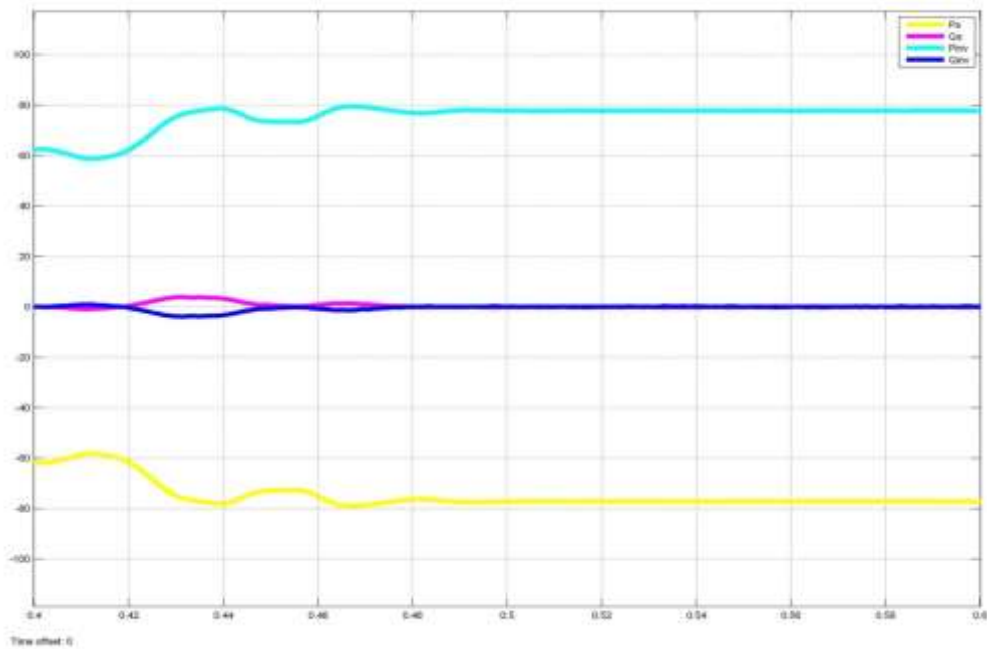


Figure 6: Injecting active power in no-load condition and low intensity of light

5.3. Analyzing inverter characteristics in loaded condition:

At $t=0$ active power of local load increases to 50kW and its reactive power to 30 kVAR. As power of load increases, injected power to the grid decreases and generated reactive power of the inverter increases to 30kVAR and power factor increases automatically but apparent power exceed the allowed apparent power according to [2] and [10]. We must have this in mind that output power is devoid of limiter and filter.

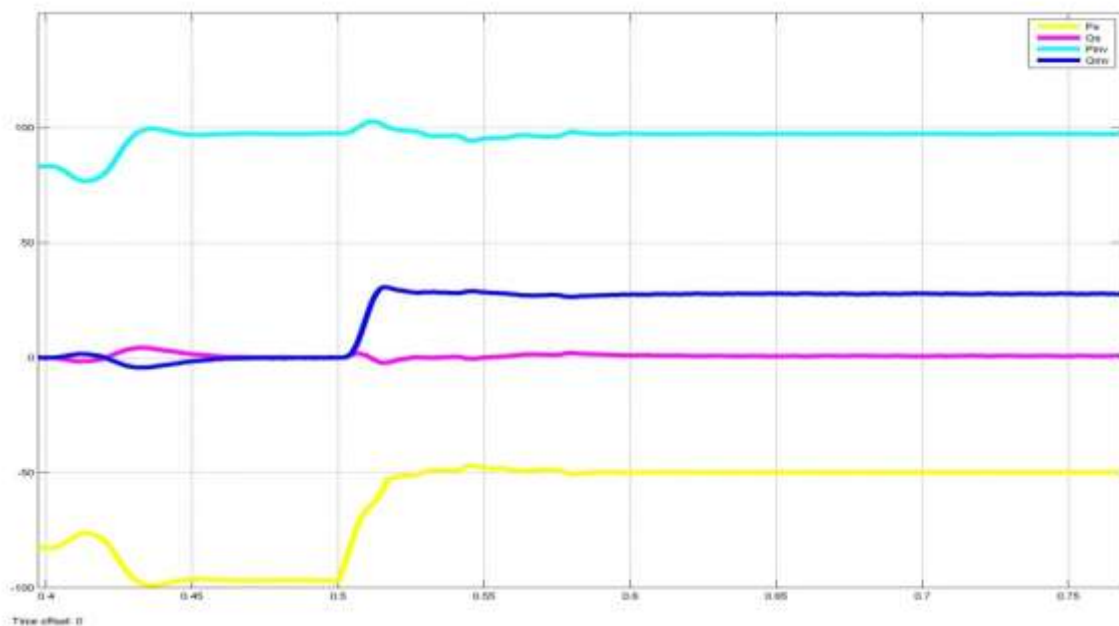


Figure 7: load increase at $t=0.5s$ and its effects on active and reactive power

In above figure, apparent power in inverter is 100kVA but according to equation [12] the absorbed power from the inverter is 104kVA that damages the inverter. The other problem in [2] is that it is devoid of filter. Since current control is performed according to α and β , it is impossible to use a low pass filter which causes current imbalance because of ohmic-inductive load, as depicted in the following figure.

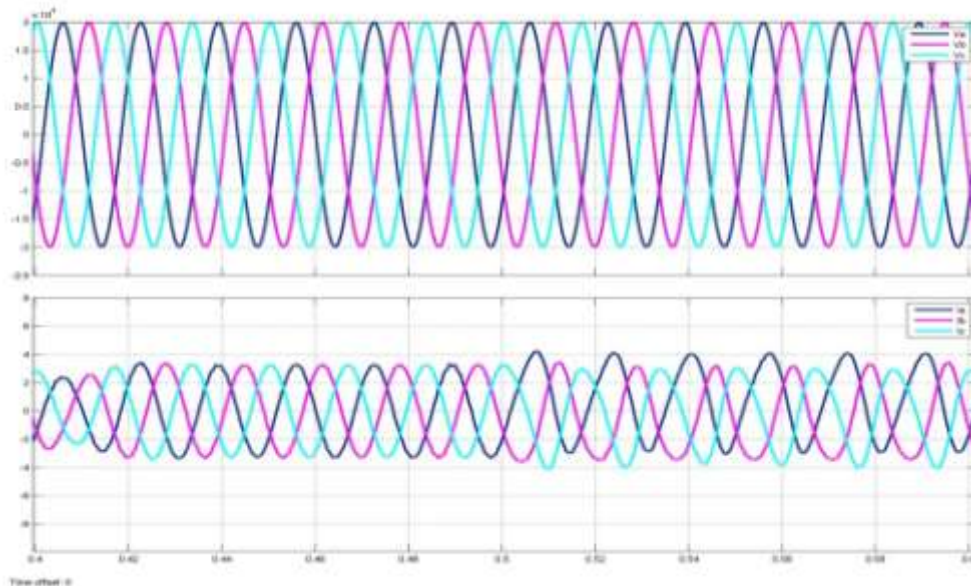


Figure 8: Injected voltage and current to the grid and the effect of inductive load on current

Because of imbalanced current in [10], THD rises accordingly. THD of the circuit after connecting the load is shown in figure9. Correcting power factor and injecting reactive power to the grid increase current imbalance and pollution of the grid.

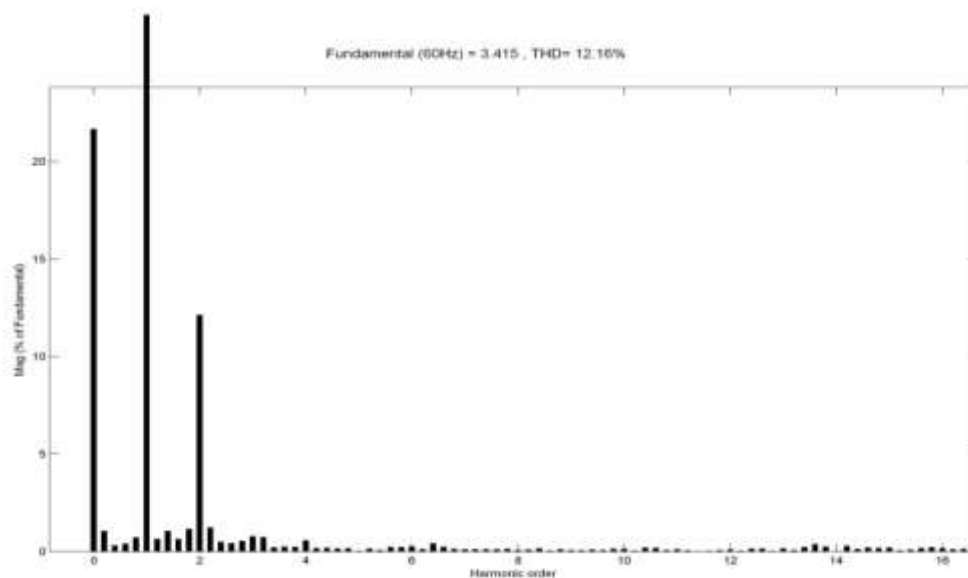


Figure 9: Analyzing THD of injected current to the grid in $P_{eL}=50\text{kW}$ and $P_{QL}=30\text{kvar}$ condition

5.4. Analyzing inverter characteristics when the load changes:

When there are different loads connected to the grid, power factor correction is performed according to the load and this occurs when the inverter has enough capacity to correct power factor; changing of power can be seen in figure. As it is illustrated in figure10, first level load including 50kW of active power and 30kVAR of reactive power is connected in $t=0.4\text{s}$. Injected power to the grid decreases as much as 50kW and absorbed power from the grid for power factor correction increases to 30kVAR. At $t=0.7\text{s}$ a load including 20kW of active power and 10kVAR of reactive power is connected that decreases injected power as much as 20kW and in addition to power factor correction, absorbed reactive power from the inverter increases 40KVAR. Finally injected power to the grid decreases from 80kW to 10kW and reactive power absorbed from inverter increases 40kVAR.

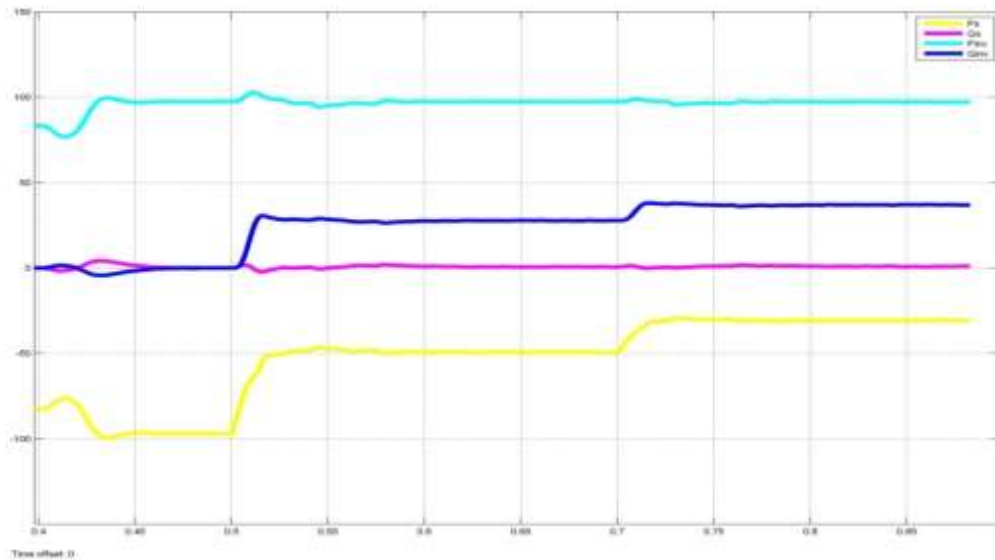


Figure 10. Power increment in two levels: a. at $t=0.5s$ and b. at $t=0.7s$

5.5. Analyzing inverter characteristics with load, filter and limiter circuit:

As stated above, in [2] inverter current control is done in $\alpha\beta$ frame so using a low pass filter for reducing unwanted fluctuations is too hard. In this paper the control is done in $d-q$ frame. Regarding to constant behavior of main signal, distortions can be controlled or eliminated using a low pass filter. In addition to using this filter, according to figure 11, a limiter circuit is inserted before i_q that causes inverter to work in allowed power range in all loading conditions.

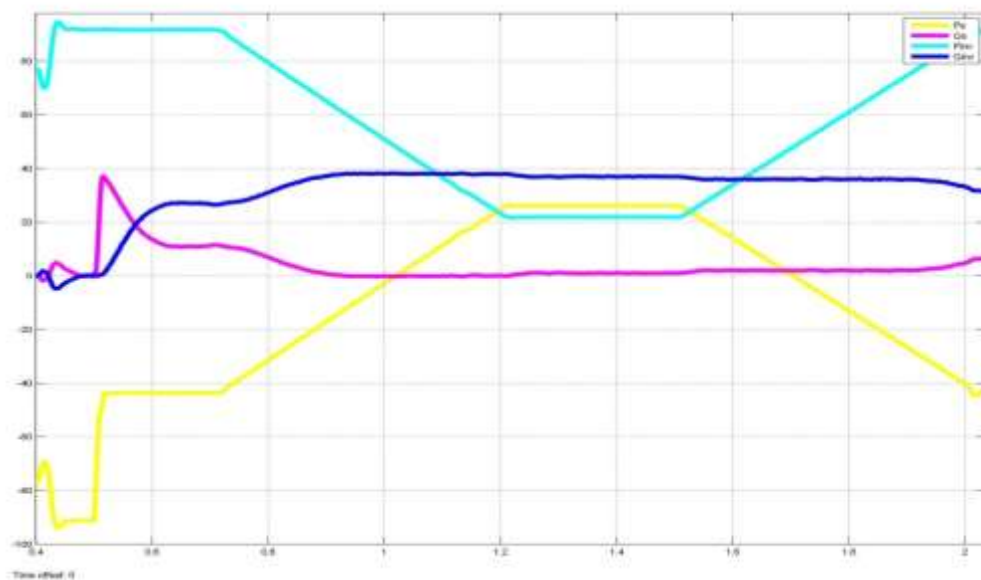


Figure 11. Output power of inverter and the grid

In figure 11 when maximum power is being injected, this limiter circuit prevents inverter to inject reactive power. The inverter is permitted to increase reactive power (according to demand of the load) just when injected active power is reduced because of low intensity of light or other reasons. It can be seen how power is injected to load and the grid in low and high intensity of light conditions. Using filter leads to balancing current that is illustrated in figure 12.

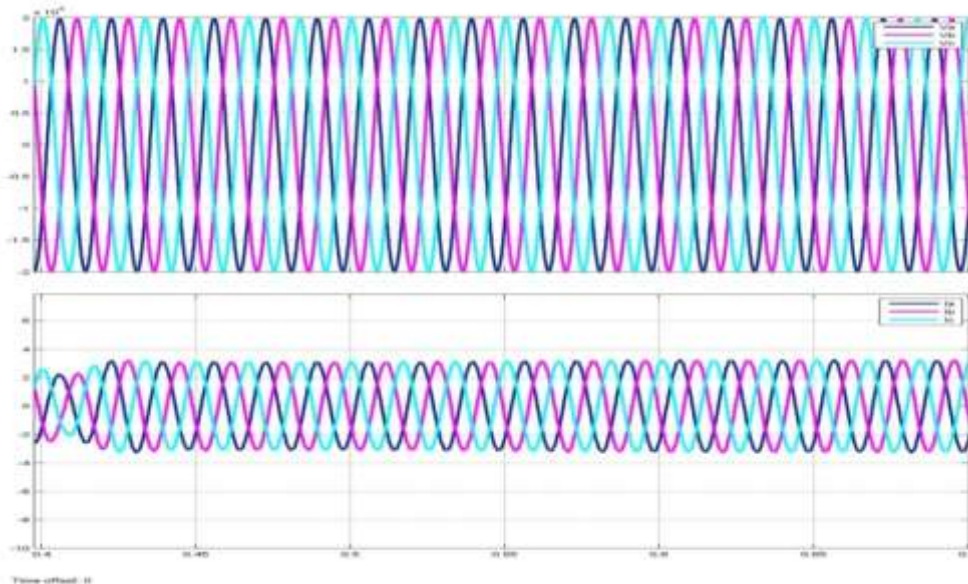


Figure 12. Output voltage and current after using filter and limiter

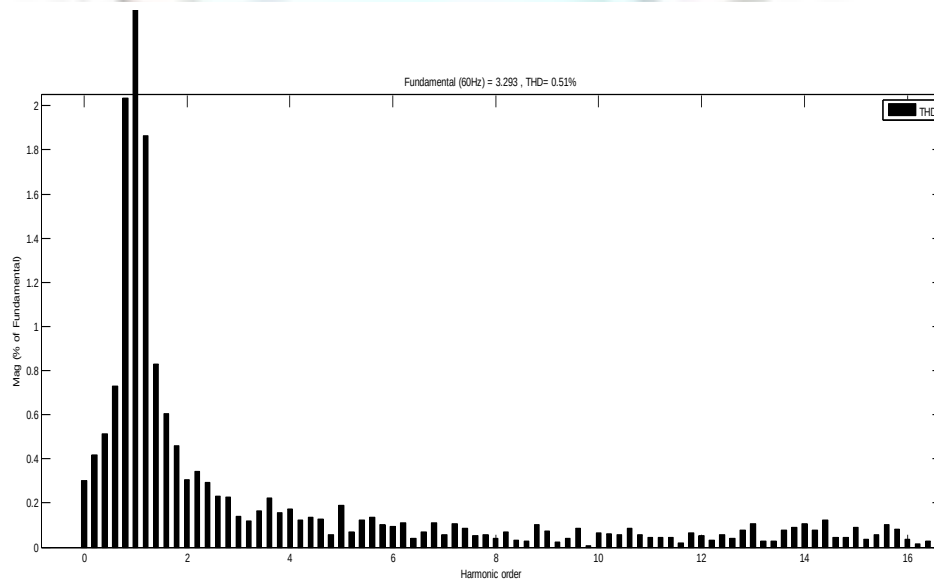


Figure 13: THD of circuit when $P_{eL}=50\text{kW}$ and $P_{QL}=30\text{kvar}$ and using filter and limiter

Conclusion

In this paper a control strategy is proposed for current control of PV inverter that controls maximum generated active power and reactive power compensation of local load simultaneously. The main idea is to utilize inverter for reactive power injection during active power decrement. Using a low pass filter and power limiter in control system, produced oscillations due to unbalanced load are eliminated and inverter works in safe condition. Simulation results show the proposed method to be viable in controlling inverter.

References

- [1]. Chung-Chuan Hou, Chih-Chung Shih, Po-Tai Cheng, Ahmet M. Hava, Common-Mode Voltage Reduction Pulsewidth Modulation Techniques for Three-Phase Grid-Connected Converters, IEEE transactions on power electronics, vol. 28, no. 4, April 2013.

- [2]. Georgios Tsengenes, Thomas Nathenas, Georgios Adamidis," A three-level space vector modulated grid connected inverter with control scheme based on instantaneous power theory", *Simulation Modelling Practice and Theory* 25 (2012) 134–147.
- [3]. S. Kouro, K. Asfaw, R. Goldman, R. Snow, B. Wu, and J. Rodríguez, NPC Multilevel Multistring Topology for Large Scale Grid Connected Photovoltaic Systems, 2010 2nd IEEE International Symposium on Power Electronics for Distributed Generation Systems.
- [4]. Georgios A. Tsengenes, Georgios A. Adamidis, Study of a Simple Control Strategy for Grid Connected VSI Using SVPWM and p-q Theory, XIX International Conference on Electrical Machines - ICEM 2010, Rome.
- [5]. César Trujillo Rodríguez, David Velasco de la Fuente, Gabriel Garcerá, Emilio Figueres, and Javier A. Guacaneme Moreno, Reconfigurable Control Scheme for a PV Microinverter Working in Both Grid-Connected and Island Modes, *IEEE transactions on industrial electronics*, vol. 60, no. 4, april 2013.
- [6]. A. Ravi, P.S. Manoharan, J. Vijay Anand, Modeling and simulation of three phase multilevel inverter for grid connected photovoltaic systems, *Solar Energy* 85 (2011), 2811–2818.
- [7]. Miguel Castilla, Jaume Miret, Antonio Camacho, José Matas, and Luis García de Vicuña, Reduction of Current Harmonic Distortion Three-Phase Grid-Connected Photovoltaic Inverters via Resonant Current Control, *IEEE transactions on industrial electronics*, vol. 60, no. 4, april 2013.
- [8]. Miguel Castilla, Jaume Miret, José Matas, Luis García de Vicuña, and Josep M. Guerrero, Linear Current Control Scheme With Series Resonant Harmonic Compensator for Single-Phase Grid-Connected Photovoltaic Inverters.
- [9]. Riad Kadri, Jean-Paul Gaubert, and Gerard Champenois, An Improved Maximum Power Point Tracking for Photovoltaic Grid-Connected Inverter Based on Voltage-Oriented Control, *IEEE transactions on industrial electronics*, vol. 58, no. 1, january 2011.
- [10]. Georgios Tsengenes, Georgios Adamidis, A multi-function grid connected PV system with three level NPC. inverter and voltage oriented control, *Solar Energy* 85 (2011) 2595–2610.
- [11]. Tony R. Kuphaldt, *Lessons In Electric Circuits, Volume II – AC*, Sixth Edition, last update July 25, 2007.
- [12]. Reza Iravani, Amirnaser Yazdani, *VOLTAGE-SOURCED CONVERTERS IN POWER SYSTEMS*, IEEE, Wiley, 2010.
- [13]. M.(E). Rashid, *Industrial Electronics (Circuits, Components and Applications)*, AR Sedaghat, B. heroes, issued facade, 2013.