

Modeling, simulation and control of three-phase three level multilevel inverter for grid connected photovoltaic system

SERKAN SEZEN*, ENGIN ÖZDEMİR^a

Balıkesir University, Altınoluk Vocational School, Atatürk Street No:103 Altınoluk/Balıkesir

^aKocaeli University, Faculty of Technology, Department of Energy Systems Engineering, 41380 Umuttepe Kocaeli

This paper presents a control for a three phase three-level neutral point clamped inverter (NPC) for grid connected photovoltaic (PV) system. The maximum power point tracking (MPPT) is capable of extracting maximum power from the photovoltaic (PV) array connected to each DC link voltage level. The MPPT algorithm is solved by Perturb&Observe method. The MPPT system is integrated with the DC-link controller so that a DC–DC converter is not needed and the output shows accurate and fast response. Synchronous Reference Frame (dq) Control Strategy is used for grid-connected PV system so that PI controllers are used to control easily DC-link voltage, active and reactive currents. The validity of the system is verified through the simulations with MATLAB/Simulink.

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1. Introduction

In recent years, the use of renewable energy resources instead of pollutant fossil fuels and other forms has increased. Photovoltaic generation is becoming increasingly important as a renewable resource since it does not cause in fuel costs, pollution, maintenance, and emitting noise compared with other alternatives used in power applications [1].

Higher power equipments require higher voltages, which limit the maximum DC voltage level. Therefore a new family of multilevel inverters has emerged as the solution for solar applications, as the PV array is directly connected to each level of the DC link. Different types of topologies are presented in the literature [2,3]. This paper uses the NPC topology since it has the advantages such as: (i) DC-link capacitors are common to three phases. (ii) Switching frequency can be low and (iii) reactive current and negative phase sequence current can be controlled.

Several methods of modulation techniques such as selective harmonic elimination PWM, sinusoidal PWM, space vector modulation, sigma delta PWM, closed loop modulation techniques exist to control the inverter [3].

The amount of power generated by a PV generator depends on the operating voltage of the PV array. The maximum power operating point changes with insulation level and temperature. The PV system operates at its highest efficiency at the maximum power point. In order to increase the efficiency, MPPT controllers are used. Such controllers are becoming an essential element in PV systems. Different tracking control strategies such as perturbation and observation, incremental conductance, parasitic capacitance, constant voltage, neural network, and fuzzy logic control have been proposed to extract

maximum power from the PV array. In this paper, perturbation and observation method is used to improve energy conversion efficiency under different environmental conditions.

The main aim is to control the active and reactive power in an inverter connected to the grid. Several methods have been found for the power control of multilevel inverters. Most of them are focused on current control algorithms whose output is modulated for switching the inverter. The whole system is simulated under standard climatic conditions (1000 W/m², 25 °C) in MATLAB and the irradiance is varied from 1000 W/m² to 700 W/m² at a time of 2nd sec. The use of PI controller makes easy to directly control the power of the grid connected PV system [4].

The proposed system consists of a PV array connected to the three phase three-level NPC through a DC bus which is connected to an ideal grid as shown in Fig. 1.

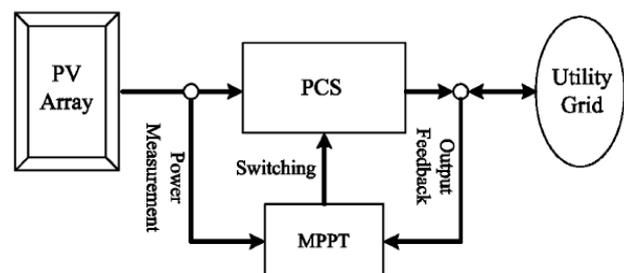


Fig. 1. PV grid connected system.

2. PV array modeling

The PV array used in the proposed system is Kaneka G-EA060 and it is simulated using a current-input model. In this model, a PV cell is represented by a current source in parallel with a diode and a series resistance as shown in Fig. 2.

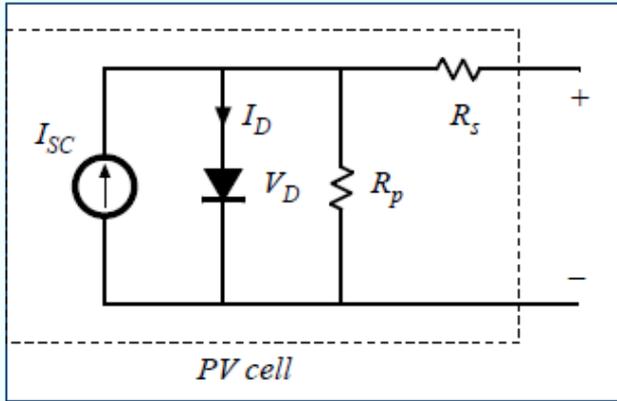


Fig. 2 PV cell circuit model.

Model parameters, in both cases, are the Standard PV module data-sheet parameters: short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), rated current at maximum power point (I_R) and rated voltage at MPP (V_R) under standard test conditions (1kW/m², 1.5 AM, 25°C). A bypass diode (a single diode across the entire module) can be included. Temperature effects are not modeled. The parameters of solar array G-EA060 at nominal operating conditions is shown in the Table 1 and Matlab model is shown in Fig. 3.

Table 1 Parameters of solar modul G-EA060 at STC

Typical electrical data under STC	
Nominal peak power Pmax	60.0 Wp
Nominal voltage Vmpp	67.0 V
Nominal current Impp	0.90 A
Open-circuit voltage Voc	92 V
Short-circuit current Isc	1.19 A

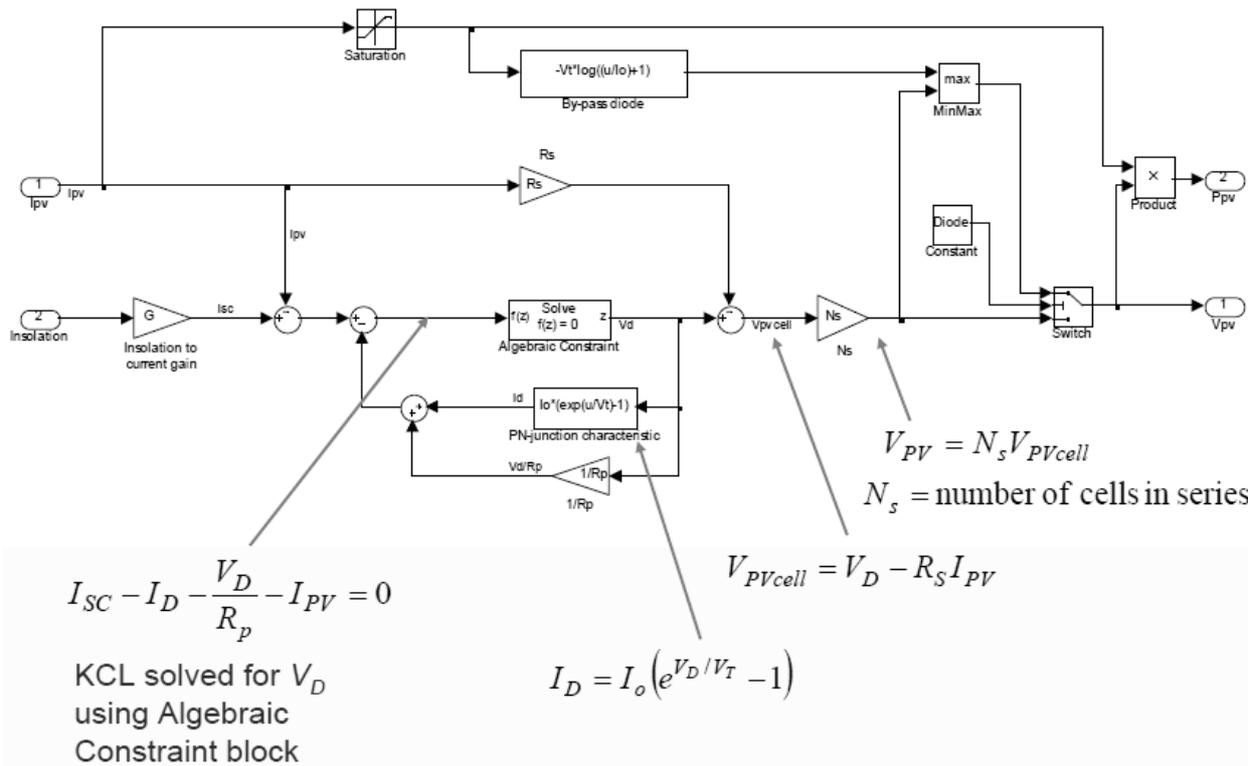


Fig. 3 Current-input PV module model.

3. Three-level inverter modeling and simulation

Multilevel inverter structures have been developed to overcome shortcomings in solid-state switching device ratings so that they can be applied to high-voltage electrical systems. The multilevel voltage source inverters' unique structure allows them to reach high voltages with

low harmonics without the use of transformers. This makes these unique power electronics topologies suitable for flexible ac transmission systems (FACTS) and custom power applications [4]. The use of a multilevel converter to control the frequency, voltage output (including phase angle), and real and reactive power flow at a dc/ac interface provides significant opportunities in the control of distributed power systems.

The general structure of the multilevel inverter is to synthesize a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. The multilevel NPC inverter starts from three levels. The NPC inverter is also called a diode clamped multilevel inverter. An m-level NPC inverter typically consists of m-1 capacitors on the DC bus and produces m-levels of the phase voltage. A three phase three-level NPC inverter is used in this paper and its Matlab model is shown in Fig. 5. Each of the phases of the inverter shares a common DC bus, which has been subdivided by two capacitors into three levels. The voltage across each capacitor is V_{dc} , and the voltage stress across each switching device is limited to V_{dc} through the clamping diodes.

PWM strategies used in a conventional inverter can be modified in multilevel inverters. Different PWM techniques are applied for controlling the active devices in a multilevel inverter [5]. The most popular technique is, which uses several triangle carrier signals and one reference, or modulation, signal per phase. In this paper Sinusoidal PWM technique is used to generate PWM control signals to the inverter. Fig. 4 shows the principle of the PWM method for a multilevel inverter. The sine wave amplitude determines modulation factor, and one modulation factor generates only one pattern of output pulse width.

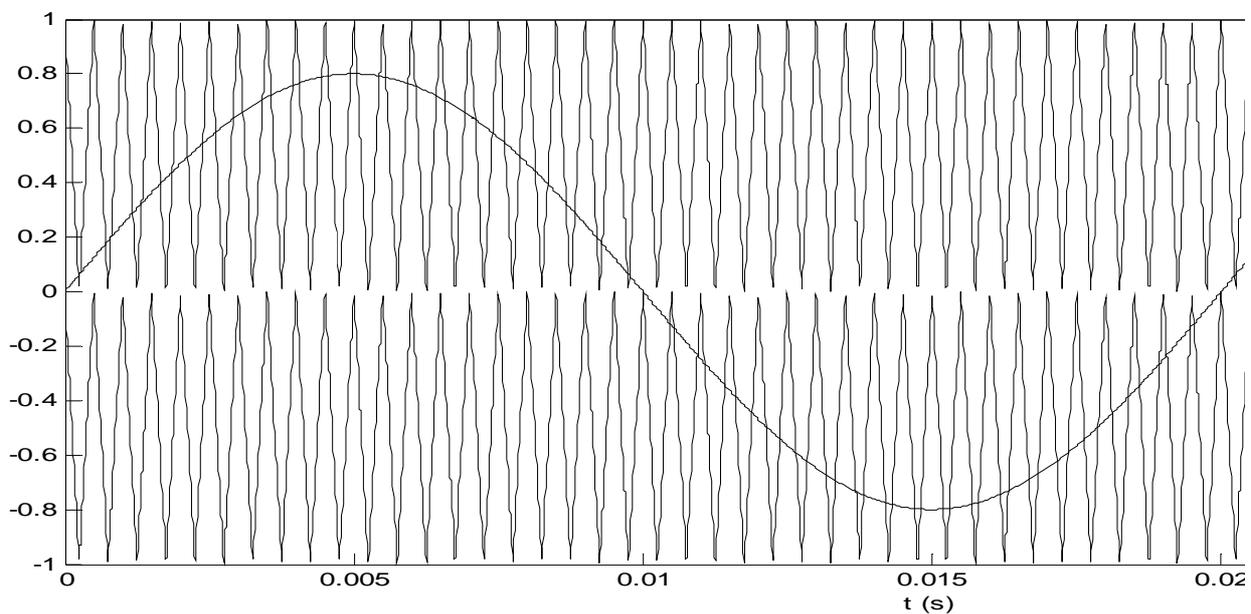


Fig. 4 Inverter modulation signals ($M = 0.8$).

In general, modulation index (M) for n level multilevel inverter is given in the following equation:

$$M = \frac{A_m}{(n-1) \cdot A_c} \quad (1)$$

where A_m is the maximum value of reference voltage (V_{ref}) and A_c is the peak to peak value of triangle wave (V_c). Modulation index should be maintained in between 0 and 1 in order to maintain low harmonic distortion. In order to produce sinusoidal current with low THD level, a sinusoidal PWM is used in this paper since it is one of the most effectual techniques.

4. Maximum Power Point Tracker (MPPT) modeling

Tracking the maximum power point (MPP) of a photovoltaic (PV) array is usually an essential part of a PV system. As such, many MPP tracking (MPPT) methods have been developed and implemented. The methods vary in complexity, sensors required, convergence speed, cost, range of effectiveness, implementation hardware, popularity, and in other respects [4].

In this paper, having the advantages of easy application, independence of the PV module type, compatibility to analog and digital control systems, [7] MPPT problem is solved by Perturb&Observe method. Fig. 6 shows Electrical characteristics of the solar cell to a particular insolation.

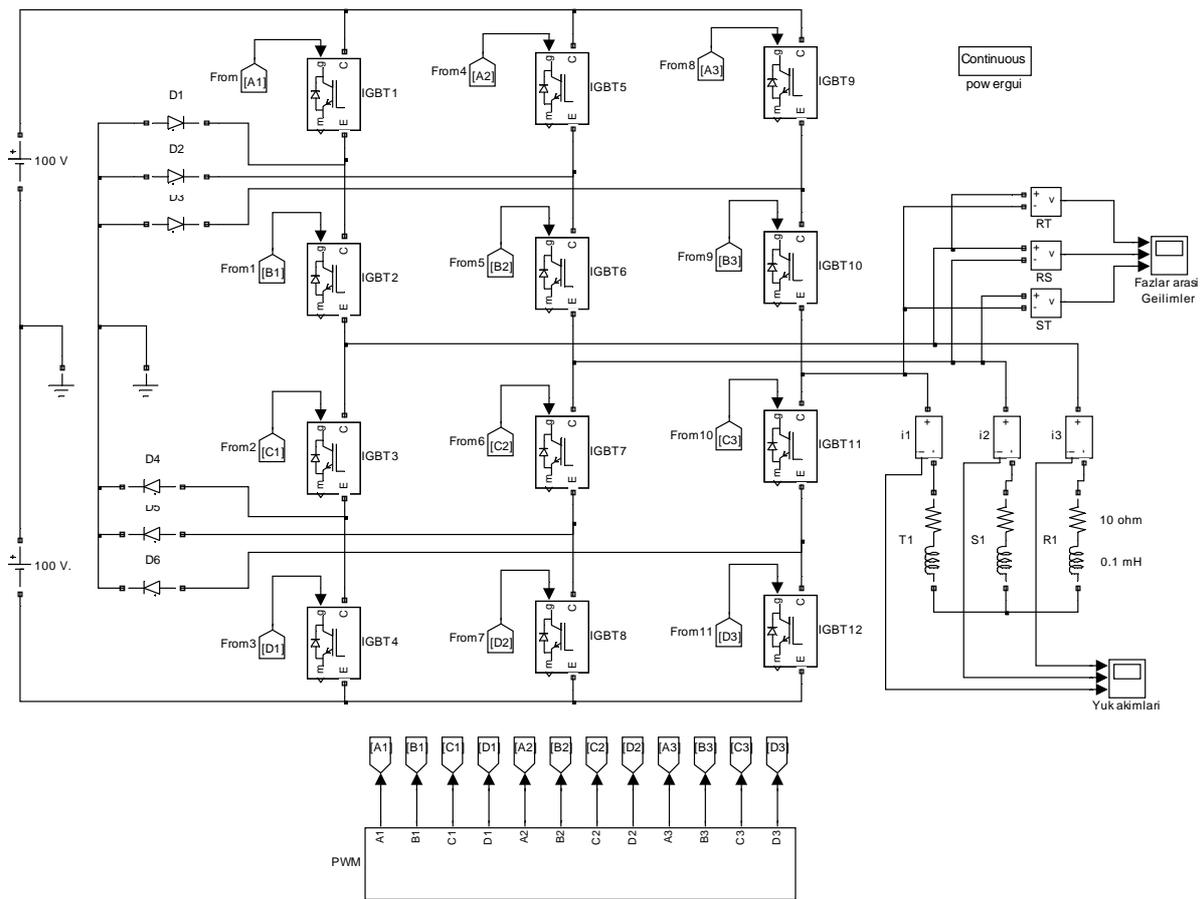


Fig. 5 Three-level three phase diode clamped inverter model.

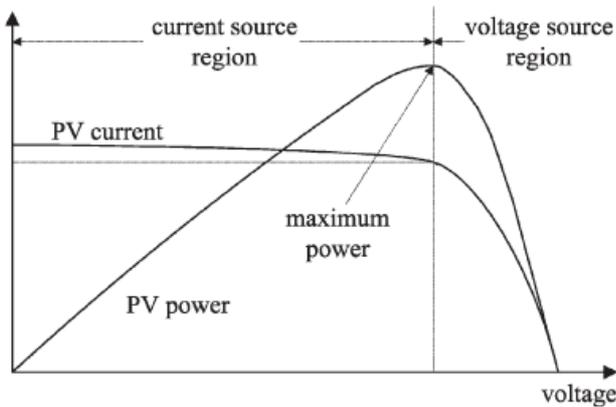


Fig. 6 Electrical characteristics of the solar cell to a particular insolation.

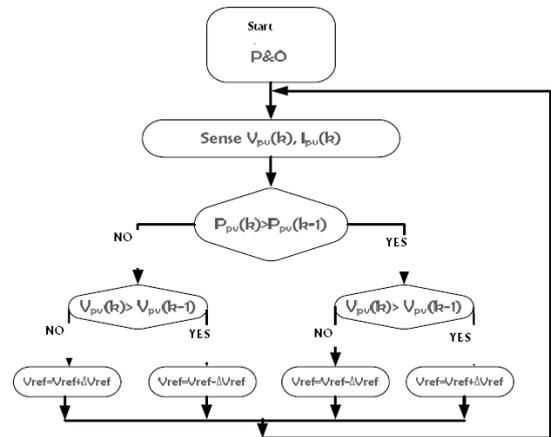


Fig. 7. Perturb&Observe method algorithm

Sampling time for the MPPT system is defined as 20 ms. Reference voltage of DC Bus voltage controller is determined by the MPPT. So there is no need to DC-DC converter in this system. Perturb&Observe method algorithm is shown in Fig. 7. and MPPT Matlab / Simulink model is shown in Fig. 8.

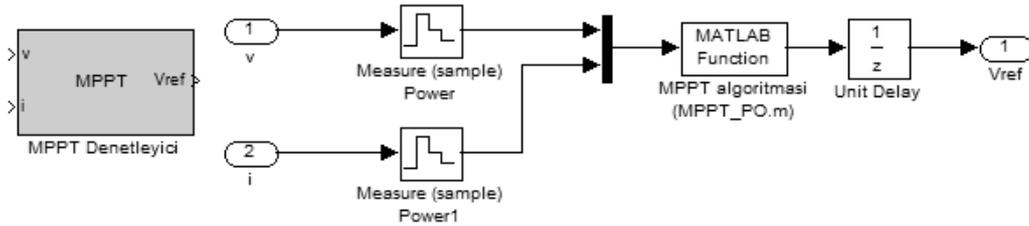


Fig. 8 Perturb&Observe method algorithm.

5. Control strategy

As the number of grid-connected renewable energy systems increased, new and compelling standards have emerged about power quality, safety, and islanding. As a result, grid-connected systems must be controlled to ensure that these requirements.

A general structure for distributed systems is illustrated in Fig. 9. The input power is transformed into electricity by means of a power conversion unit whose configuration is closely related to the input power nature. The electricity produced can be delivered to the local loads or to the utility network, depending where the generation system is connected. One important part of the distributed system is its control. The control tasks can be divided into two major parts.

1) Input-side controller, with the main property to extract the maximum power from the input source. Naturally, protection of the input-side converter is also considered in this controller.

2) Grid-side controller, which can have the following tasks:

- Control of active power;
- Control of reactive power;
- Control of dc-link voltage;
- Ensure high quality of the injected power;
- Grid synchronization.

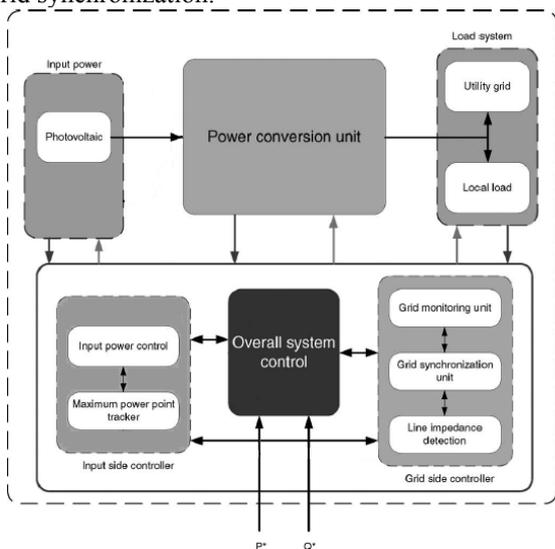


Fig. 9 General structure for grid-connected photovoltaic systems.

The control strategy applied to the grid-side converter consists mainly of two cascaded loops. Usually, there is a

fast internal current loop, which regulates the grid current, and an external voltage loop, which controls the dc-link voltage [4]. The current loop is responsible for power quality issues and current protection; thus, harmonic compensation and dynamics are the important properties of the current controller. The dc-link voltage controller is designed for balancing the power flow in the system. Usually, the design of this controller aims for system stability having slow dynamics. Control strategies vary by reference frame that control variables described in: Synchronous Reference Frame Control, Stationary Reference Frame Control and Natural Frame Control

5.1 Synchronous Reference Frame Control Algorithm

Synchronous reference frame control, also called *dq* control, uses a reference frame transformation module, e.g., *abc* → *dq*, to transform the grid current and voltage waveforms into a reference frame that rotates synchronously with the grid voltage. By means of this, the control variables become dc values; thus, filtering and controlling can be easier achieved [8]. A schematic of the *dq* control is represented in Fig. 10. In this structure, the dc-link voltage is controlled in accordance to the necessary output power. Its output is the reference for the active current controller, whereas the reference for the reactive current is usually set to zero, if the reactive power control is not allowed. In the case that the reactive power has to be controlled, a reactive power reference must be imposed to the system.

The *dq* control structure is normally associated with proportional–integral (PI) controllers since they have a satisfactory behavior when regulating dc variables. The transfer function of the controller can be written as:

$$TF = Kp + \frac{Ki}{s} \tag{2}$$

where *Kp* is the proportional gain and *Ki* is the integral gain of the controller.

Since the controlled current has to be in phase with the grid voltage, the phase angle used by the *abc* → *dq* transformation module has to be extracted from the grid voltages. As a solution, filtering of the grid voltages and using arctangent function to extract the phase angle can be a possibility. In addition, the phase-locked loop (PLL) technique became a state of the art in extracting the phase angle of the grid voltages in the case of distributed generation systems.

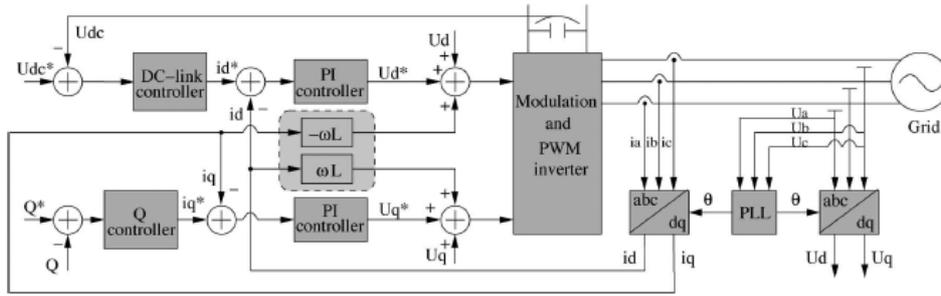


Fig. 10 General structure for synchronous rotating frame control structure.

In this paper, Synchronous Reference Frame Control is used to control photovoltaic system and controller is modeled in Matlab environment. How to calculate the PI coefficients for current and voltage controllers in the model, are summarized in Table 2. Equations for the

parameters set out in this table are shown in Equation 3. [6]

In case of using L-type filter with a value of 0.15 Ω resistance and 15.6 mH inductance at grid side and 2200 μF capacity at DC link side, calculation of PI coefficients according to Table 2, are shown in Table 3.

Table 2 Design of Current and Voltage PI controller

	No filter	Filter $1/(1 + nT_s s)$
Current PI		
$k_{p,c}$	33% σ_c	$[100/(3+n)]\% \sigma_c$
$T_{I,c}$		$\tau \rightarrow$ limit current overshoot $10\tau \rightarrow$ high grid disturbance rejection
Voltage PI		
$k_{p,v}$		20% σ_v 2% $\sigma_v \rightarrow$ better decoupling from the current loop
$T_{I,v}$	$17 T_s$ $65 T_s \rightarrow$ better decoupling from the current loop	$[(3+n)/3]17T_s$ $[(3+n)/3]65T_s$

$$\left. \begin{aligned} \sigma_c &= \frac{L + L_g}{T_s} \\ \tau &= \frac{L + L_g}{R + R_g} \\ \sigma_v &= \frac{C}{T_s} \end{aligned} \right\} \quad (3)$$

Table 3 Calculation parameters and PI Coefficients of current and voltage controller.

Calculation Parameters	Value
σ_c	124.8
τ	0.104
σ_v	17.6
Current Controller Parameters	Value
Kp_c	41
Ti_c	0.104
KI_c	400
Voltage Controller Parameters	Value
Kp_v	0.352
Ti_v	$8.25 \cdot 10^{-3}$
KI_v	43

6. Results

Simulations performed using MATLAB/Simulink for the proposed system is shown in Fig. 11, 12 and 13. The Sinusoidal PWM switching strategy consists of one reference signal and two triangular waves of 8 KHz. Irradiance is step down from 1000 W/m^2 to 700 W/m^2 at 2nd second. Fig. 11 shows line voltage of three level inverter. Fig 2 shows the synchronization between current injected to grid and grid voltage for one phase. Fig. 3 shows one PV panel power and reference voltage (produced by MPPT) variation.

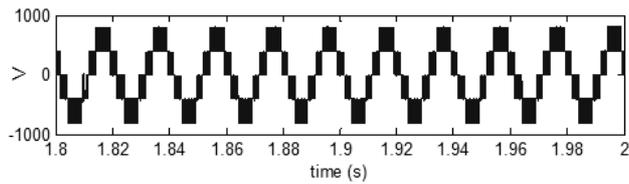


Fig. 11 Line voltage of three level inverter

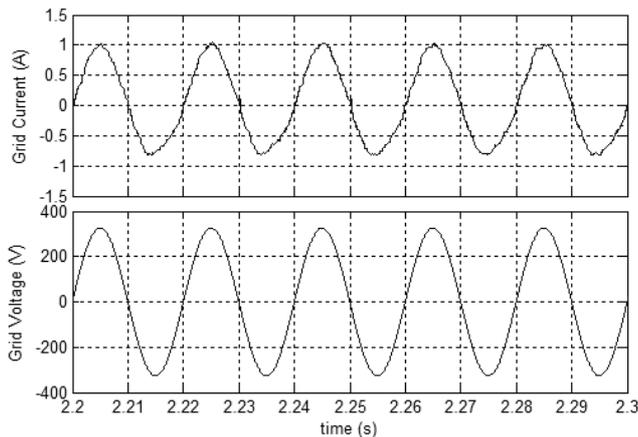


Fig. 12 Synchronization between current injected to grid and grid voltage.

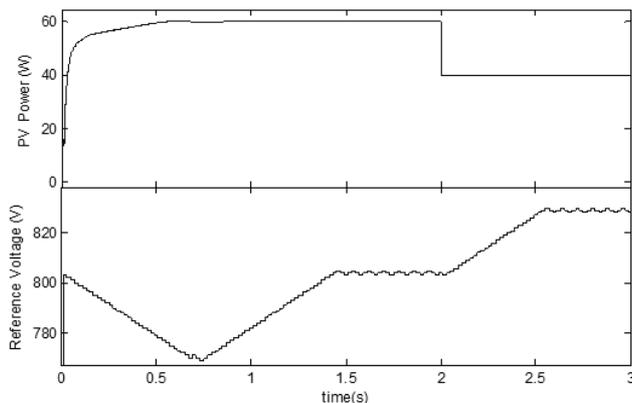


Fig. 13 PV panel power and reference voltage (produced by MPPT) variation.

7. Conclusions

This paper presents a three phase multilevel inverter for grid connected photovoltaic systems. The configuration for the proposed system was designed first, and simulated using MATLAB/simulink. The acceptable results are achieved in terms of MPPT, grid synchronization, and inverter control for the proposed three-level NPC inverter. Irradiance is step down from 1000 W/m^2 to 700 W/m^2 at 2nd second and grid connected photovoltaic system adapted to this change about 0.5 second successfully.

Acknowledgements

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*Corresponding author: serkansezzen@balikesir.edu.tr