Design and Simulation of three phase Inverter for grid connected Photovoltic systems

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***Abstract*— Grid connected photovoltaic (PV) systems feed electricity directly to the electrical network operating parallel to the conventional source. This paper deals with design and simulation of a three phase inverter in MATLAB SIMULINK environment which can be a part of photovoltaic grid connected systems. The converter used is a Voltage source inverter (VSI) which is controlled using synchronous d-q reference frame to inject a controlled current into the grid. Phase lock loop (PLL) is used to lock grid frequency and phase. The design of low pass filter used at the inverter output to remove the high frequency ripple is also discussed and the obtained simulation results are presented.**

Keywords- VSI Inverter, PLL, d-q refrance frame, grid connected system.

I. INTRODUCTION

The continuously increasing energy consumption, overloads the distribution grids by creating problems such as outages, grid instability, deterioration of power quality, power security etc. To balance the energy demand and generation, renewable energy resources such as Photovoltaic (PV), Wind, and Biomass could be a good solution. Among these, solar energy is considered to be one of the most useful sources because it is free, abundant, pollution free and maintenance free. Since the generated voltage from PV is DC, we need inverter for converting DC voltage from PV to AC before connecting it to grid. Grid is a voltage source of infinite capability. The output voltage and frequency of inverter should be same as that of grid frequency and voltage. The output of grid connected inverter can be controlled as a voltage or current source and pulse width modulated (PWM) voltage source inverters (VSI) are most widely use in PV systems.

The work done related to PV grid connected systems published so far [6]-[7] reveals how an inverter should be designed and output should be synchronized with the grid. Different control strategy to control grid current using p-q theory and d-q theory with phase lock loop (PLL) control has been discussed in those papers.

The work presented here is about the simulation of a VSI where the output current of inverter is controlled in synchronously rotating d-q reference frame. PLL is used to synchronize grid with PV. The relevant standards and design of the entire system, simulink models and results obtained are presented in the subsequent sections.

II. DEMANDS AND STANDARDS

In order to connect an inverter to the grid, the generated power has to comply with the standards given by utility companies. The standards like IEEE1547, IEC61727 & ENC61000-3-2 deals with issues like power quality, detection of islanding operation, amount of injected current into grid, total harmonic distortion (THD) etc. IEEE1547 & IEC61727 standard puts the limitation on maximum amount of injected current into the grids. This limits are very small (0.5% and 1% of rated output currents) and such small values are very difficult to measure. This problem can be resolved by introducing a line frequency transformer between inverter and grid [1]. Assuming that both grid voltage and grid current contain only fundamental components and they are in phase the instantaneous power (p_{grid}) injected into the grid is given by (1).

$$p_{grid} = 2 * P_{grid} * Sin^2(\omega_{grid} * t) \quad (1)$$

Where P_{grid} is the average power injected into the grid, ω_{grid} is the angular frequency and t is the time [1].Table I. deals with different standards and THD limits of connecting 10KW and 30 KW to the grid.

TABLE I. STANDARDS OF INTERCONNECTION OF PV SYSTEM TO THE GRID

Issues	***IEC61727***		***IEE1547***	
Nominal Power	10KW		30KW	
Harmonis currents Limits	Harmonics	THD	Harmonics	THD
	3-9 11-15 17-21 23-33	4% 2% 1.5% 0.6%	3-9 11-15 17-21 23-33 (>)35	4% 2% 1.5% 0.6% 0.3%
Maximum current THD	5.0%		5.0%	

III. Design Details of the System

A. *Inverter and Transformer*

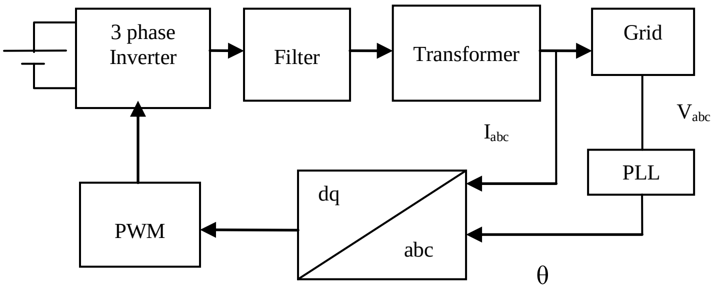

Fig.1 Block diagram of the system

The block diagram of the grid connected inverter system is given in Fig.1. The three phase full bridge inverter topology is the most widely used configuration in three phase systems. The inverter selected is current controlled voltage source inverter that has an amplitude modulation index (m_a) of 0.9. MOSFETS are used as the switching element which is operated at a frequency of 20 KHz. Bi-polar PWM technique is used in which switches in each pair are turned ON and OFF simultaneously and output voltage varies between $-V_{dc}$ and $+V_{dc}$, where V_{dc} is the input voltage of inverter which is considered as battery as shown in block diagram. The output of each leg depends only on input voltage and switch status and is independent of load current. The output voltage required is 415V rms at the grid.

Transformer steps up the inverter output voltage. Besides this, it provides isolation and prevents injection of dc current in to the grid Generally delta-star transformer configuration is used in grid connected system because the third harmonic will get circulated in delta and does not enter in the grid. The design is for feeding 1KW power generated by PV to grid. This means transformer should provide 1KW power to the grid. So transformer rating is selected as 1250VA with a secondary voltage of 415 volt (L-L).

B. *LC Fiter*

Output voltage wave is synchronized with the grid voltage. So the PWM inverter will inject ripple current in to the grid. The output LC filter is connected to remove high switching frequency components from output current of inverter[2].The filter is designed taking into account the following parameters for the grid and inverter as shown in Table II. The value of L is design based on current ripple. Smaller ripple results in lower switching and conduction losses.

TABLE II. DESIGN PARAMETERS

Grid line voltage	V_{L-L}=415V
Grid phase voltage	V_{ph}=240 V
DC source voltage	V_{dc}= 250V
Output power fed to grid	P_n =1000 W
Grid Frequency	f = 50 Hz
Switching frequency	f_s= 20 KHz

Typically the ripple current can be chosen as 10% - 15% of rated current. Considering 10% ripple at the rated current the designed value of inductor (L) in the system [3]-[4] is given by (2)

$$\Delta i_{Lmax} = \frac{1}{8} * V_{dc} / L * f_s \quad (2)$$

The capacitor C is designed based on reactive power supplied by the capacitor at fundamental frequency. In this design reactive power is chosen as 15% of the rated power [3] is given by (3)

$$C = 15\% * P_{rated} / 3*2\pi f * V^{2}_{rated} \quad (3)$$

C. *Control Stratergy*

The control strategy applied for inverter consists of two control loops. Usually there is a fast inner control loop which controls grid current and an external voltage loop which control dc link voltage. The current control loop is responsible for power quality issues like low THD and good power factor, whereas voltage control loop balances the power flow in the system [5]. Synchronous reference frame control also called d-q control uses a reference frame transformation abc to dq which transforms the grid current and voltages into d-q frame. The transformed voltage detects phase and frequency of grid, whereas transformed current controls the grid current. Thus the control variables becomes dc values, hence filtering and controlling becomes easier [6].

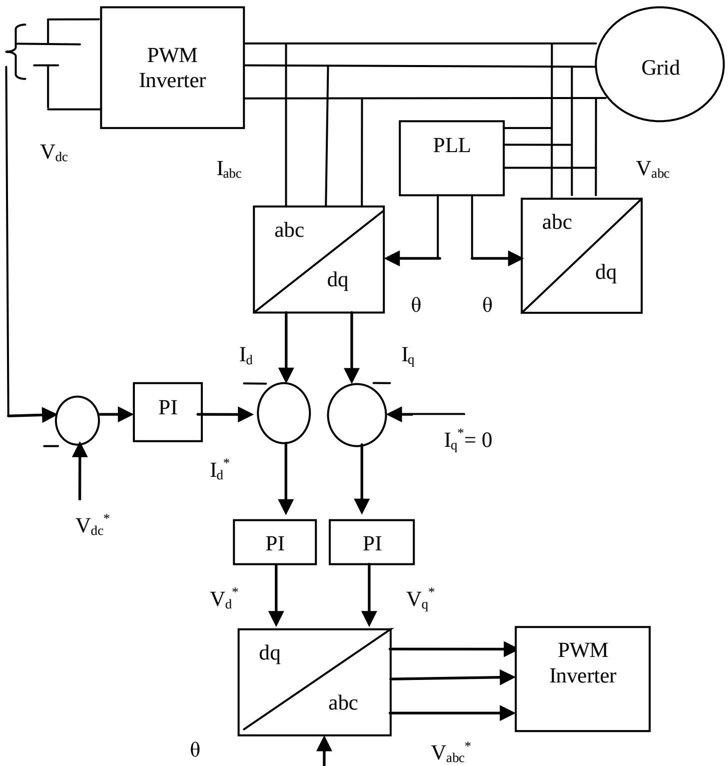

Fig.2 General structure for synchronous rotating d-q reference frame control.

The schematic of the d-q control is shown in Fig.2. The DC link voltage is actually fed from PV. For the simulation, battery is used as input of inverter. The reference for active current control is set by DC link voltage, whereas reactive power control reference is set to zero, as reactive power control is not done here. If reactive power has to be controlled a reference must be set in the system for that also.

D. Phase lock loop(PLL)

Grid synchronizations plays important role for grid connected systems. It synchronizes the output frequency and phase of grid voltage with grid current using different transformation. Different methods to extract phase angle have been developed and presented in many papers up to now [8]-[11] PLL techniques causes one signal to track another one. It keeps an output signal synchronized with a reference input signal in frequency and phase. In three phase grid connected system PLL can be implemented using the d-q transformation and with a proper design of loop filter.

Fig.3 shows the block diagram of three phase PLL, where V_{abc} is the sensed grid voltage which is transformed in to DC components using coordinate transformation abc-dq and the PLL gets locked by setting V_d^* to zero. The loop filter PI is a low pass filter. It is used to suppress high frequency component and provide DC controlled signal to voltage controlled oscillator (VCO) which acts as an integrator. The output of the PI controller is the inverter output frequency that is integrated to obtain inverter phase angle θ. When the difference between grid phase angle and inverter phase angle is reduced to zero PLL becomes active which results in synchronously rotating voltages $V_d = 0$ and V_q gives magnitude of grid voltage.

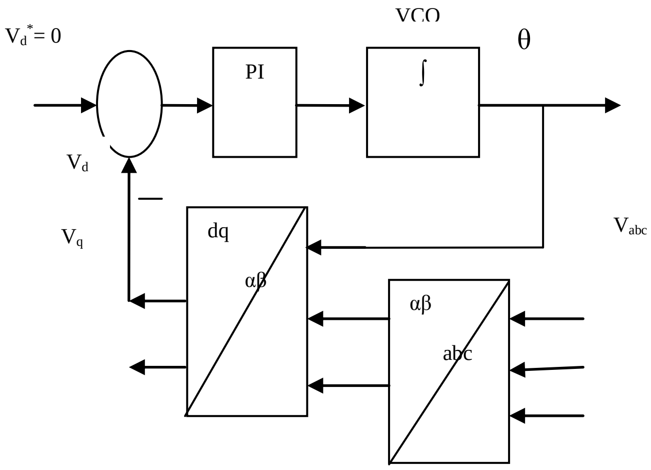

Fig.3 General structure of three phase d-q PLL

IV. SIMULATION RESULTS

Based on the design, simulation of the entire system is done in Simulink. PLL model is shown in Fig.4 and the entire system model is shown in Fig.8. PLL is developed for grid voltage of 415 V rms.

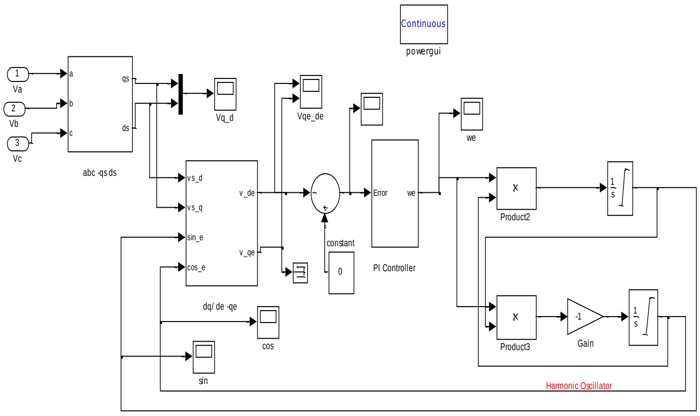

Fig.4 PLL model

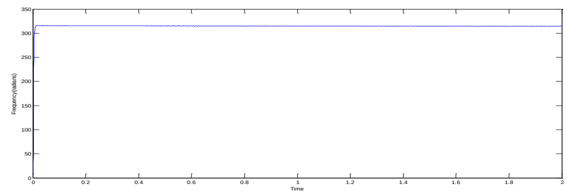

Fig.5 Output frequency obtained from PLL

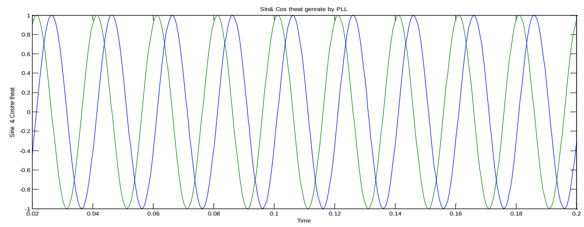

Fig.6 Sin & Cos wave generated by PLL

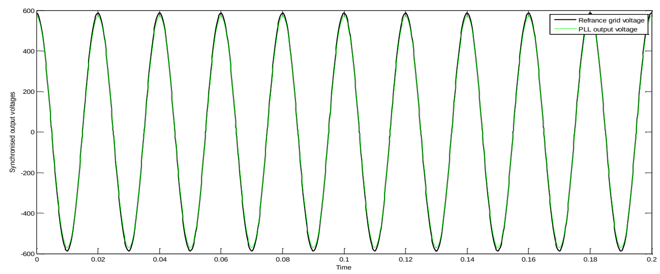

Fig.7 Synchronization between reference grid voltage & PLL output voltage

The inverter output frequency locked by PLL is 314 rad/sec which is 50 Hz as shown in Fig.5.The simulation results of PLL shows that when grid phase angle equals to inverter phase angle, the error at the output of phase detector becomes zero and equals to reference V_d^* and lock is set by PLL. The output controlled signal from PI regulator to VCO generates the *Sinθ* and *Cosθ* required for abc-dq and dq- abc transformation in control loop as shown in Fig.6. PI controller gain was varied to obtain zero phase error and to detect accurate inverter phase angle. Synchronization between output of inverter phase and grid phase angle is achieved by locking PLL not only at zero crossing but at every instant of time between 0 to 2π. Synchronization between rotating reference frame PLL output voltage and grid voltages is shown in Fig.7. The abc to dq current transformation results in dc component of I_d and I_q components. The I_d component controls the active current necessary to feed active power to grid. The DC magnitude of I_d obtained in simulation is approximately equal to 2.42 Ampere. The reference voltages obtained by inverse transformation are compared with triangular wave which generates PWM signal required by inverter. In closed loop current control of inverter, the active power fed by inverter to grid is 1000 Watt as shown in Fig.10.The voltage at the output of inverter remains always constant and obtained magnitude in simulation is 415*√2 which is 586.89Volt(peak to peak) as shown in Fig.9.

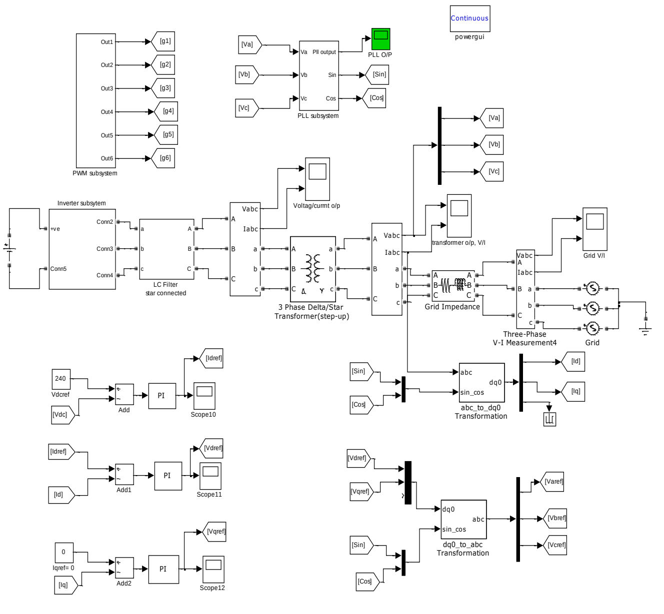

Fig.8 Model of inverter connected to grid

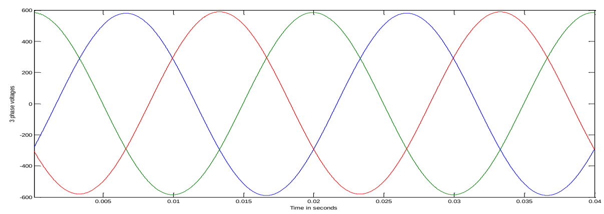

Fig.9 Three phase voltage fed by inverter to grid

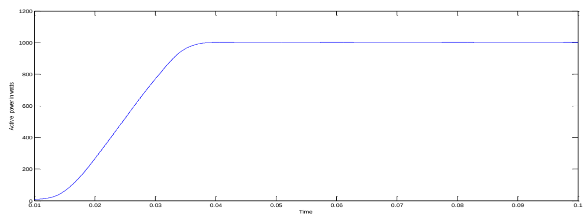

Fig .10 Average active power fed to grid is 1000 Watt

The FFT analysis of output current of inverter shows that THD is very low and obtained simulation results is 1.78%.

V. CONCLUSION

The design of the system is carried out for feeding 1KW power to the grid The Inverter is controlled in order to feed active power to the grid, using synchronous d-q transformation. PLL is used to lock grid frequency and phase. The phase detection part of PLL is properly done by using dq transformation in the three phase system.

The FFT analysis of the inverter output current shows that the THD is within limits and the controlled injected current generates three phase balance current which controls power at the output of the transformer.

To simulate the actual grid connected PV system, the PV model, dc to dc converter model and the control of the dc to dc converter should be included in place of the battery source.

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