Design and Simulation Three Phase Inverter for Grid Connected Photovoltaic Cells

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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. MPPT (Maximum Power Point Tracking) algorithm will be developed for synchronizing the micro grid with the main grid. In addition, the voltage control of the micro grid plays a great role in the synchronization system performance.**

Keywords - VSI Inverter, PLL, d-q reference frame, MPPT, grid connected inverter.

I. INTRODUCTION

The continuously increasing energy consumption overloads the distribution grids, which leads to 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 PV cells, Wind, Biomass and Tidal could be a good solution. Among these, solar energy is considered to be one of the most useful sources because it is free, profuse, pollution free, low installation cost, maintenance free. Large photovoltaic systems ranging from 20kW to 1MW are becoming more common, increasing the importance of three-phase grid connected inverters to the photovoltaic industry. The grid-tied inverter differs from the stand-alone unit. It provides the interface between the photovoltaic array and the utility.

The grid coupled inverter conditions the power output of the photovoltaic array. It also serves as the system's control mechanism and the means through which the site-generated electricity transfer the utility lines [1]. Circuit topologies, conversion efficiency, MPPT, power quality, anti-islanding and cost are the main design considerations that need to be examined. Most high power PV systems are three phase and all PV systems are coupled with the three phase distribution network. The average model of the inverter has been simulated with constant current mode control.

Since the generated voltage from PV cell 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 VSI are most widely use in PV systems.

The work done related to PV grid connected systems published so far [2]-[3] 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 PLL control has been discussed in those papers.

MPPT is a technique that grid connected inverters, solar battery chargers and analogous devices use to get the maximum possible power from one or more photovoltaic devices, typically solar panels, though visual power transmission systems can benefit from similar technology[4]. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analyzed based on the I-V curve. It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions. MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion, filtering, and regulation for driving various loads.

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 consequent 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 and

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% to 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 [5]. 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 (2.1).

$$P_{grid} = 2P_{grid}\sin^2(\omega_{grid} * t) \qquad (2.1)$$

Where P_{grid} is the average power injected into the grid, ω_{grid} is the angular frequency and t is the time [5] deals with different standards and THD limits of connecting 10KW and 30 KW to the grid.

III. DESIGN DETAILS OF THE SYSTEM

A. Inverter and Transformer

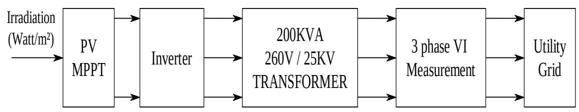

Fig.1 Block diagram of grid connected inverter

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 VSI that has an amplitude modulation index (ma) of 0.9. IGBT are used as the switching element which is operated at a frequency of 20 KHz. IGBTs can be modeled as ideal on/off switches that represent the inverter's discrete switching behaviors. The switching model not only confines the voltage and current ripple, it also includes dead time and delays that are based on the IGBT device characteristics and gate-driver design in the actual hardware. Bi-polar PWM technique is used in which switches in each pair are turned ON and OFF simultaneously and output voltage varies between –Vdc and +Vdc, where Vdc 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 260V 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 200KVA power generated by PV to grid. This means transformer should provide 200KVA power to the grid. So transformer rating is selected as 200KVA with a secondary voltage of 260 volt (L-L).

B. LC Filter

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 inverter's output [6]. The value of L is design based on current ripple. Smaller ripple results in lower switching and conduction losses.

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 [7]-[8] is given by (2.2

$$\Delta i_{L\max} = \frac{1}{8} * \frac{V_{dc}}{L * f_s} \qquad (2.2)$$

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 [7] is given by (2.3)

$$C = 15\% * P_{rated} / 3 * 2\pi f * v_{rated}^{\ 2} \qquad (2.3)$$

C. Inverter Modelling

The knowledge for three phase inverter is gaining more practical importance in the recent past. Besides, the technology for three phase inverters can be extended to single phase inverters. Generally, the overall power-conditioning system includes front end conversion and regulation. Examples of this are DC/DC conversion for prime movers with DC output which are given by fuel cell, PV Cells, Battery, or AC/DC conversion for prime movers with AC output of micro turbines and sterling engines. The input to the inverter is a regulated DC source in both these cases. The input to the inverter is modelled as a DC voltage source in the model. A simplification in the model is the inverter output filters, which could have different variations in practical applications; for example, the output filter could include L, or LCL, or LC plus a transformer, with or without harmonic filters. In the analysis done, an L only (inductor) filter is considered. dq realization and controller concepts have been used for the modelling of the three phase PV inverter [9-12].

D. Grid Coupled PV Inverter Model In MATLAB

The block diagram of grid connected inverter model developed in simulink is shown in Fig.2.

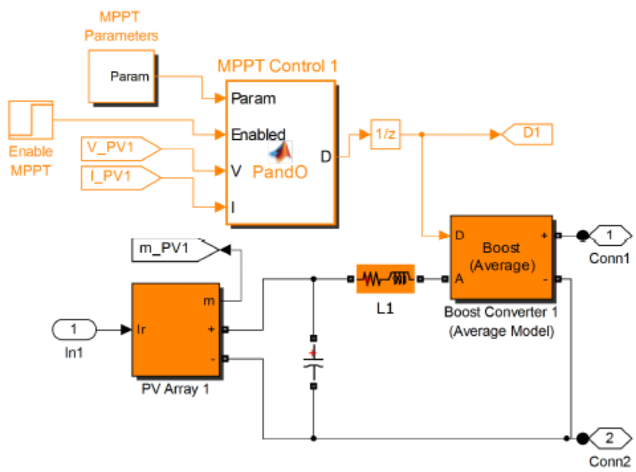

Fig.2 MPPT control of Grid connected Sun Power SPR-305-WHT module in MATLAB/Simulink

IV. CONTORL MODES

There are two basic control modes for the grid connected inverters, constant current control and constant power control.

It is still uncertain whether an inverter should be permitted to regulate voltage when connected to the grid. The current IEEE 1547 standard [13] does not allow DG to actively regulate voltage, but there is suggestion that DG voltage regulation may have some positive impact on the grid. For the detailed analysis, constant current controlled inverters are used to exhibit the concepts, which can be easily extended to constant power controlled inverters. In constant power control, the power loops are outside the current loops. In the case of reactive power injection, the power factor could be the reactive power reference. The inverter output power will follow the power references. A variation of the constant power control is the stable DC bus voltage control. In this, instead of using an active power reference, DC bus voltage is regulated while the input to the inverter is a constant power source. The power control mode is more popular in modern digitally controlled inverters. For the purpose of this work, constant current control has been used. The control design for a three phase inverter can be realized either in ABC (stationary) or in dq (rotating) frames. In constant current control, the inverter output currents are regulated to the given current references which come from design specification. The controller has been created with key functional blocks like ABC/dq transformation, dq PLL, summing function, linear regulator in the form of a proportional-integral controller and dq/ABC transformation.

Many functions to deal with practical issues are not modelled in the standard model, e.g. negative sequence regulation, dq decoupling and device protection. Park's transformation, mentioned in (4.1), was used to convert the ABC reference frame to dq reference frame (synchronous frame) and vice versa (zero reference frame is neglected). A controller modelled in the dq reference frame can eliminate steady state error.

$$Pi=\frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta-\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (4.1)$$

Utility interconnected PV systems do not regulate voltage; they inject current into the utility. Therefore, the voltage operating range for PV inverters is selected not as a voltage regulation function but as a protection function that reacts to irregular utility situations. As long as the magnitude of current injection from PV inverters on a utility line remains less than the load on that line, the utility's voltage regulation devices will continue to operate normally.

In a case where the PV current injection on a utility line exceeds the load on that line, then corrective action is required, because the voltage regulation devices do not normally have directional current sensing capability. Small PV systems (≤10kW) should be capable of operating within the limits normally experienced on utility distribution lines. If the inverter installation is electrically close enough to the PCC to allow negligible voltage difference between the inverter and the PCC, then the 110% of nominal voltage trip point will apply to the inverter terminals as well as the PCC. However, some systems may have installation restrictions that do not allow negligible voltage difference between the inverter and the PCC. In such cases, it is recommended that the inverter stop to energize the utility lines whenever the voltages at the PCC diverge from the allowable voltage operating range. PV systems have a fixed frequency operating range of 49.3 to 50.5 Hz. The test points for determining proper operation of the frequency trip function should be 49.2 Hz and 50.6 Hz. When the utility frequency is outside the range of 49.3-50.5 Hz, the inverter should cease to energize the utility line within six cycles. The purpose of the allowed time delay is to ride through short term disturbances to avoid excessive annoyance tripping. Non islanding PV inverters are designed for connection as a parallel source to a utility service.

In addition to fixed over frequency, under frequency, over voltage, and under voltage trips described, this type of inverter includes a way to shut down when the utility source is not present (the non islanding feature). Once the fixed frequency and voltage limits have been confirmed, the inverter is tested to determine if it can maintain stable operation in the presence of a utility source.

A utility source means any source capable of maintaining an island within the recommended voltage and frequency gap. Voltage should be at least 3% inside the most restrictive voltage trip limits. Frequency should be at least 0.25 Hz inside the most restrictive frequency trip limits.

PV systems are protected against the vast majority of potential islanding situations by voltage and frequency revealing schemes. However, it is possible that circumstances may exist on a line section that has been isolated from the utility and contains a balance of load and PV generation that would allow continued operation of PV systems. Such circumstances would require a load generation balance so that both frequency and voltage remain within the trip limits. Although such a load balance is supposed as a low-probability event, the potential impact of such an occurrence is great enough that this distributed resource islanding has been the subject of numerous studies and much research.

After an out-of-bounds utility event that has caused the PV system to stop energizing the utility line, continuous normal voltage and frequency have to be maintained by the utility to re-energize the line. A minimum of 5 minutes is desirable, at which time the inverter can reconnect the PV generation system to the utility automatically [14].

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 [2]. 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.

V. 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 paper[15] - [18]. A PLL technique uses one signal to track another one. It keeps an output signal synchronized with a reference input signal in frequency and phase. In three phases grid connected system PLL can be implemented using the d-q transformation and with a proper design of loop filter.

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 Vd = 0 and Vq gives magnitude of grid voltage.

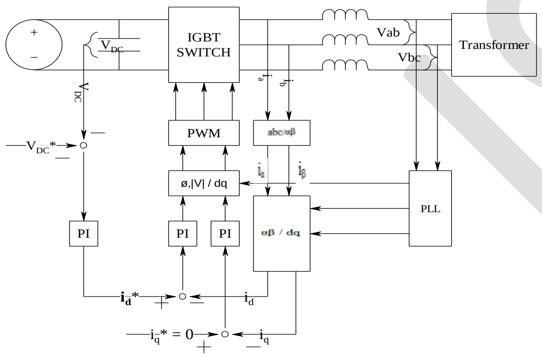

Fig.3 Voltage control of inverter with unity pf.

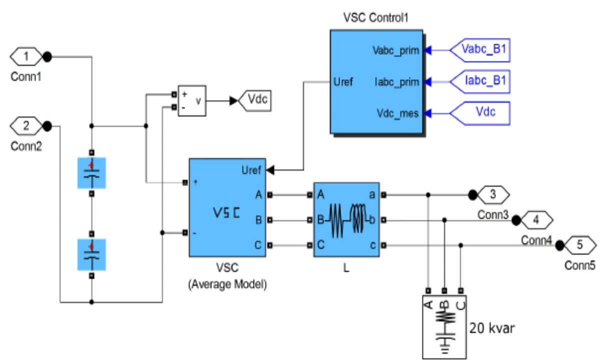

Fig.4 Matlab model of grid connected inverter with control

TABLE 1
SIMULATION RESULT WITH VARIOUS IRRADIATION

A	B	C	D	E	F
1000	273.68	368.43	100.72	0.46	500.2
900	272.15	330.83	90.03	0.46	500.01
800	270.76	293.26	79.4	0.46	500.01
750	268.73	275.78	74.11	0.46	499.99
700	267.66	257.2	68.84	0.47	499.98
600	266.56	218.94	58.36	0.47	500.01
500	263.57	275.78	47.97	0.48	500.01
400	260.09	144.96	37.7	0.48	500
300	255.47	107.97	27.58	0.49	500
250	253.17	89.24	22.59	0.49	500
200	248.94	107.97	17.67	0.51	500
100	240.27	33.61	8.07	0.52	500
50	240.17	13.96	3.35	0.52	500

A	G	H	I	J	K
1000	18996.9	3.2	90.5	0.5	0
900	18996	2.8	80.9	0.5	0
800	18995.1	2.5	71.4	0.4	0
750	18994.6	2.3	66.6	0.4	0
700	18994.2	2.2	61.8	0.4	0
600	18993.3	1.8	52.4	0.3	0
500	18992.5	1.5	43	0.2	0
400	18991.5	1.2	33.7	0.2	0
300	18990.7	0.9	24.6	0.1	0
250	18990.2	0.7	20	0.1	0
200	18989.8	0.6	15.6	0.1	0
100	18989	0.2	6.83	0.1	0
50	18989	0.1	2.53	0	0

Here
A = Ir-radiation (in Watt / m²)
B = Vpv =Voltage of photo voltaic array
C = Ipv = Current of photo voltaic array
D = Ppv(in KW) = Power of photo voltaic array
E = Duty cycle of converter
F = V_{DC} = DC bus voltage
G = Vbus = Bus voltage
H = Ibus = Bus current
I = P_{grid} (in KW) = Power of grid
J = Id = Direct axis current
K = Iq = Quadrature axis current

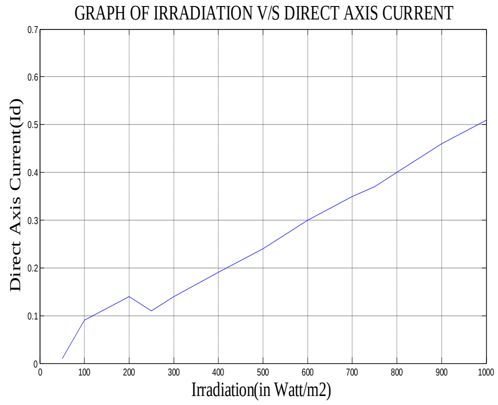

Fig. 5 Graph of Irradiation v/s I_d

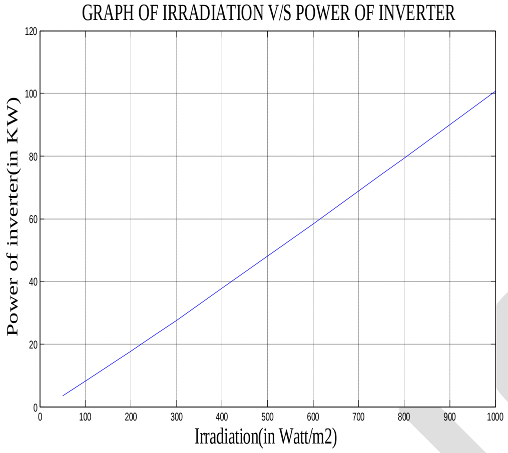

Fig. 6 Graph of Irradiation v/s $P_{inverter}$

VI. CONCLUSION

Based on the design, simulation of the entire system is done in simulink. PLL model is shown in Fig.4 and the block diagram model shown in Fig.3.

The inverter output frequency locked by PLL is 314 rad/sec which is 50 Hz. The output controlled signal from PI regulator to VCO generates the $Sin\theta$ and $Cos\theta$ required for abc-dq and dq- abc transformation in control loop as shown in Fig.3. 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. The abc to dq current transformation results in dc component of Id and Iq components. The Id component controls the active current necessary to feed active power to grid. 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 146 KW.

The design of the system is carried out for feeding 146KW 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. From above Fig 5 and 6 conclude that power of grid, power of inverter and direct axis current is linearly increase with increase the rate of irradiation. When direct axis current increase means increase in active power.

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