Design of Grid connected Photovoltaic Inverter with Resonant Harmonic Compensator

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Abstract: ***The reduction of high harmonic content in the grid side current is achieved by different harmonic compensating techniques. In order to accomplish it, selective harmonic compensation is carried out in grid-connected photovoltaic inverters by means of resonant harmonic compensators. The harmonic compensator shown in this paper is lead lag compensator. This paper shows a systematic design procedure for selecting the gains and parameters of these harmonic compensator's. Some Other factors considered in the design process include frequency deviation, grid synchronization, and harmonic profile. A design of grid connected photovoltaic inverter meeting the requirements of grid interconnection using MATLAB Simulink and selected experimental results are also reported.***

Keywords: Photovoltaic inverters, Harmonic compensator, Grid synchronization, liner current regulator.

1. Introduction

The Photovoltaic installations usually have a flexible design. Solar Photovoltaic arrays, dc/dc converters, and inverters are combined in a distributed configuration to perform the main functions, such as maximum-power-point tracking, voltage amplification, and synchronous grid-current injection. The interconnection of Photovoltaic inverters to the electrical grid is regulated by international standards. As a guidance to ensure compatible operation, these standards include factors relating to power quality, personnel safety, and equipment protection. The quality of power provided by the Photovoltaic inverter is bounded by limits on voltage, frequency, and harmonics. Deviation from these limits represents abnormal conditions and may require disconnection of the non is-landing inverter from the electrical grid [1, 2].

It consists of a bank of generalized integrators, i.e., second-order band pass filters tuned to resonate at a predefined frequency. In fact, each generalized integrator is responsible for the attenuation of an individual grid-current harmonic. Ideal generalized integrators are also used. These integrators exhibit theoretically an infinite gain at the resonance frequency, ensuring a nearly perfect harmonic elimination. However, the realization of ideal generalized integrators is sometimes not possible due to finite precision in digital systems. Thus, a damped generalized integrator is proposed in which have limited gain at the resonance frequency. This configuration is realized in digital platforms with a high accuracy and, moreover, it is well suited for alleviating some instability problems identified in ideal integrators. The design of resonant harmonic compensator's is not well documented in the literature [1-10]. The value of the generalized integrator parameters is essential for the system performance, so that a method for choosing these parameters is actually necessary. In previous works, a time-consuming trial-and-error method is normally carried out for the design of generalized integrators [9]. Some design considerations have been briefly discussed and the control parameters have been finally tuned using simulation or experimental results. In fact, there is no systematic procedure in the literature for the design of damped resonant harmonic compensator's. In this project, we present a complete design-oriented study for single-phase grid-connected Photovoltaic inverters with damped resonant harmonic compensators [5]. The effect of the compensator characteristics on the inverter performance is analyzed in detail. A set of design trade-off relating harmonic injection, frequency deviation, grid synchronization, and transient response is identified. As a result, we propose a systematic procedure for the design of damped resonant harmonic compensators compliant with the requirements on grid interconnection [11, 12]. This procedure constitutes the main contribution of this project. The need for compensator in grid connected photovoltaic inverters is: The injection of low-harmonic current to the electrical grid is regulated by international standard. In order to accomplish this standards, selective harmonic compensation is carried out in grid-connected photovoltaic inverters by means of resonant harmonic compensators. The LCL filter is used to eliminate the higher order harmonics. Thus by improving harmonic profile of a Photovoltaic system [4].

The main objectives of this paper includes: Compensators are used to reduce the low current harmonics that are injected to the electric grid. Designing the compensator's to meet the requirements for grid interconnection. The stability analysis of compensator characteristics on the inverter performance has to be analyzed. Comparing the harmonic profile with and without compensator.

2. System Description

The figure 1 shows the grid-connected PV inverter. This proposed model consists of a PV array which is acting as input to inverter which consists of inverter connected to LCL filter [4] and then which is connected to a grid as load. From grid ac voltage and current are sensed and are given to phased locked loop for synchronization of grid with the inverter output voltage. Then it is further filtered by using a compensator and it is connected to inverter. So it forms a closed loop and decreases the injection of harmonic currents into grid and improves the total harmonic distortions.

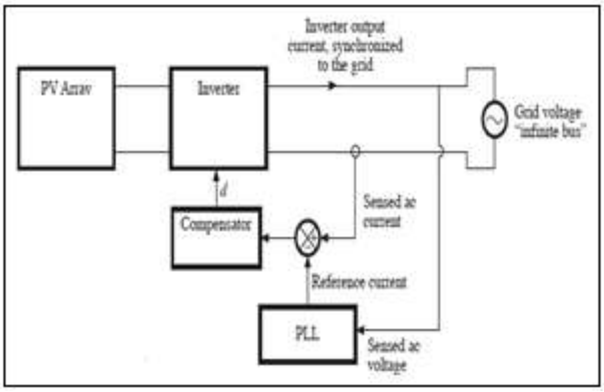

Figure 1: Proposed System

The equivalent circuit-based model is mainly used for the MPPT technologies [6]. The equivalent circuit of the general model which consists of a photo current, a diode and parallel resistor expressing a leakage current, a series resistor describing an internal resistance to the current flow. The voltage and current characteristic equation of a solar cell is given as

$$I = I_{PV} * NP - I_S * NP * (e^{[\frac{q(v+R_S(\frac{N_S}{N_P}))}{aKT}]-1}) - \frac{V + IR_S}{R_{SH}} \quad (1)$$

Where,
IPH is a photocurrent,
I_S is cell saturation of dark current,
q (= 1.6 ×10−19C) is an electron charge,
K (= 1.38 ×10−23J/K) is a Boltzmann's constant,
TC is the cell's working temperature,
A is an ideal factor,
RSH is a shunt resistance,
RS is a series resistance.

Maximum power point tracking, frequently referred to as MPPT and it is an electronic system that operates the PV modules such that the modules produce all the power they are capable of. The MPPT is not a mechanical tracking system that physically moves the modules to make them point directly at the sun. It just varies the electrical operating point of the modules so that they deliver the maximum available power. There are different types of MPPT techniques available, out of them here perturb and observer technique is used. Since, since it is suitable under uniform environmental conditions and its efficiency is high and it produces accurate results.

3. Design of Quasi Z-source inverter

The quasi z-source inverter (QZSI) is a single stage power converter derived from the Z-source inverter topology [3], employing a unique impedance network. The conventional VSI and CSI suffer from the limitation that triggering two switches in the same leg or phase leads to a source short and in addition, the maximum obtainable output voltage cannot exceed the dc input, since they are buck converters and can produce a voltage lower than the dc input voltage. In the shoot through mode [3] as shown in figure below, switches of the same phase in the inverter bridge are switched on simultaneously for a very short duration.

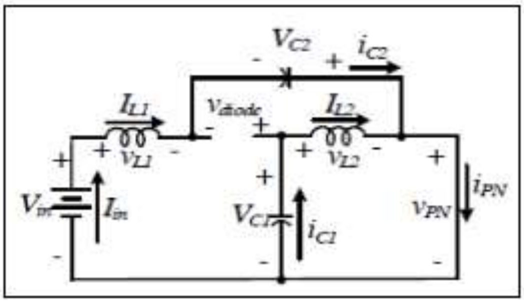

Figure 2: Equivalent circuit of QZSI in Shoot through Mode

Inductor design: During traditional operation mode, the capacitor voltage is always equal to the input voltage. So there is no voltage across the inductor. During shoot through mode, the inductor current increases linearly and the voltage across the inductor is equal to the voltage across the capacitor. The average current through the inductor is given by,

$$IL = \frac{P}{V_{dc}} \quad (2)$$

Where P is the total power and V_{dc} is the input voltage. The average current at 1kW and 150 V input is
IL (avg) = 1000/150 = 6.67A

The maximum current occurs through the inductor when the maximum shoot-through happens, which causes maximum ripple current. In this design, 30% current ripple through the inductors during maximum power operation was chosen. Therefore the allowed ripple current was 4A and maximum current is 10.67A.

For a switching frequency of 10 kHz, the average capacitor voltage is

$$V_C = (1 - \frac{T_O}{T}) * \frac{V_{dc}}{(1 - 2 * \frac{T_o}{T})} \quad (3)$$

Substitute the values in the above equation (2) the average capacitor voltage is 300V.
*L = 0.1 * 10 * 300 / 10.67 = 3mH*
So the inductance must be not less than 3mH.

Capacitor design: The purpose of the capacitor is to absorb the voltage ripple and maintain a fairly constant voltage. During shoot-through the capacitor charges the inductors and the current through the capacitor equals the current in the inductor. Therefore the voltage ripple across the capacitor is

$$V_C = IL(avg) \frac{T_S}{C} \quad (4)$$

The capacitor voltage ripple is 0.17%.

Substitute the above values in the equation the required capacitance was found to be
*C = 6.67 * 0.1 * 10 (300 * 0.0017) = 1000µF*

Hence the impedance network of the Quasi Z-Source inverter consists of an inductor of value 3mH and capacitor of 1000µF.

4. Inverter and Grid Synchronization

The power of PV will be varied by variation in irradiation. But voltage should be maintained constant at grid side.so, synchronization of grid should be done with input voltage and current i.e. PV panel voltage and current then forming the grid synchronization gives a closed loop system. This grid synchronization is needed since the input voltage and current are varied.

The relation between the dc-link voltage and current is linear and is given experimentally as follows

$$V_{dcO} = V_{dc} + K * I_{dc} \quad (5)$$

By making the power balance between the dc-link power and the power supplied to the grid with neglecting the power losses in the grid-side PWM inverter, the dc-link current I_{dc} can be calculated as follows

$$I_{dc} = \frac{V_s}{V_{dc}} * I_{sd} \quad (6)$$

Therefore, V_{dc0} can be redefined by substituting (6) in (5) as Follows

$$V_{dc0} = V_{dc} + K * V_s * \frac{I_{sd}}{V_{dc}} \quad (7)$$

The generator frequency is defines as follows

$$F = \frac{V_{dc} + K * V_s * \frac{I_{sd}}{V_{dc}}}{2.47} \quad (8)$$

The current reference i^*_{sd} of the grid-side converter is calculated from the predetermined maximum output power of the inverter according to the generator frequency which is defined by

$$P_t = K_{opt} * f^3 \quad (9)$$

Where,
K_{out} = output of slow external dc link voltage loop.
f = frequency
P_t = Maximum output power of inverter.

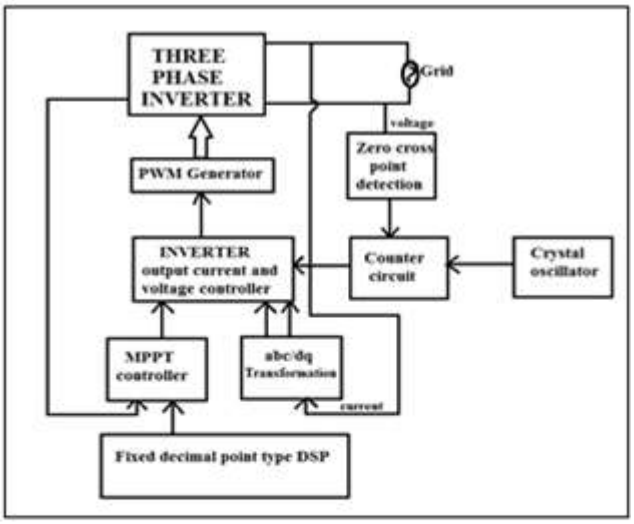

Figure 3: Circuit and control diagram of MPPT control algorithm for grid-side PV inverter.

When the losses in the proposed system are considered, i^*_{sd} can be easily set by using a lookup table in the Digital signal processing program. Based on the aforementioned principle, the control block diagram of the inverter is constructed, as shown in Figure 3. The current reference is set to achieve the desired MPPT scheme which results in the maximum active power being supplied to the grid. The current controller has fast a response as it works in a synchronous reference frame [8].

5. Design of Lead Lag Compensator

Harmonics are produced on grid side is due to following reasons

1. If generated power is equal to the load power then no harmonics are produced.
2. If generated power is greater or lesser than the load power, harmonics are produced at grid side.

To compensate that harmonics LCL filter and lead lag compensator are used. The phase-lead portion of the compensator may be used to increase the system bandwidth and achieve faster response at lower frequencies, and the phase-lag portion may be used to lower steady-state error and to reduce susceptibility to high frequency noise. Either the phase-lead or the phase-lag portions can be designed first.

$$G_c(s) = \frac{P_1 * P_2}{Z_1 * Z_2} \frac{S + Z_1}{S + P_1} \frac{S + Z_2}{S + P_2} [P_1 > Z_1 and P_2 < Z_2] \quad (10)$$

A frequency-domain analysis of the single-phase inverter grid-connected through an LCL filter is below. The resulting dynamic model of the grid current is essential for the design of the resonant harmonic compensators. In the Laplace domain, the open-loop inverter system can be modelled as

$$I_i(s) = G_1(s) * V_i(s) + G_2(s) * V_g(s) + G_3(s) * d(s) \quad (11)$$

$$I_O(s) = G_4(s) * V_i(s) + G_5(s) * V_g(s) + G_6(s) * d(s) \quad (12)$$

With V_m and T_d the amplitude of the PWM triangular signal and the computational delay time of one sampling period, respectively.

$$i_i(s) = \frac{[G_1(s) * V_i(s) + G_2(s) * V_g(s) + G_3(s) * PWM(s) * G_d(s) * H_1(s) * I_{ref}(s)]}{1 + G_3(s) * PWM(s) * G_d(s) * H_s(s)} \quad (13)$$

Using all above equations we get the dynamic model of the grid current can be expressed as

$$i_O(s) = G_7(s) * V_i(s) + G_8(s) * V_g(s) + G_9(s) * i_{ref}(S) \quad (14)$$

Where G7(s) is the input voltage to grid current transfer function, G8(s) is the grid voltage to grid current transfer function, and G9(s) is the reference signal to grid current transfer function. These functions are given by

$$G_7(s) = G_4(s) - [\frac{G_1(s) * G_6(s) * H_S(s) * PWM(s) * G_d(s)}{1 + T(s)}] \quad (15)$$

$$G_8(s) = G_5(s) - [\frac{G_2(s) * G_6(s) * H_S(s) * PWM(s) * G_d(s)}{1 + T(s)}] \quad (16)$$

$$G_9(s) = [\frac{G_6(s) * H_1(s) * PWM(s) * G_d(s)}{1 + T(s)}] \quad (17)$$

PV system loop gain;

$$T(s) = G_3(s) * (H_1(s) + H_2(s)) * PWM(s) * G_d(s) \quad (18)$$

LCL Filter Design: The LCL filter has good current ripple attenuation even with small inductance values. However, it can bring also resonances and unstable states into the system. Therefore the filter must be designed precisely according to the parameters of the specific inverter. Important parameter of the filter is its cut-off frequency. The cut-off frequency of the filter must be minimally one half of the switching frequency of the inverter, because the filter must have enough attenuation in the range of the inverter's switching frequency. The cut-off frequency must have a sufficient distance from the grid frequency too. The cut-off frequency of the LCL filter can be calculated as

$$f_{res} = \frac{1}{2*\Pi}\sqrt{\frac{L_1 + L_2}{C*L_1*L_2}} \quad (19)$$

Also,

$10f_g < f_r < \frac{fsw}{2}$

Where fg – grid frequency, fs – switching frequency.

The damping resistor Rd connected in series with filter capacitor C is calculated using the below formula

$$R_d = \frac{1}{3*c*\omega_r} \quad (20)$$

6. Simulation Results

The Simulink circuit of inverter with lead lag compensator as control block and with an LCL filter is shown in below fig 4. Here results of both without compensator and with compensator are considered. The simulation results for both are shown in following figures.

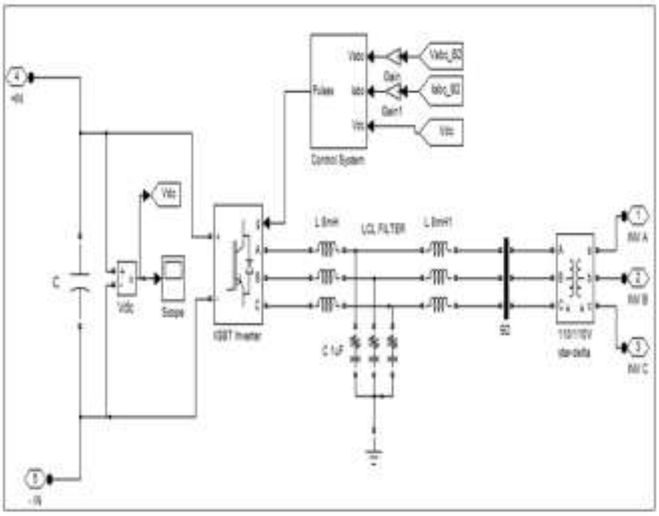

Figure 4: Simulation circuit of inverter with compensator

6.1 Grid voltage without compensator

This grid output voltage is taken when the inverter is connected to LCL filter across grid. The LCL filer improves the harmonic profile by reducing high order harmonics and reduced the total harmonic distortion as 20.16%.

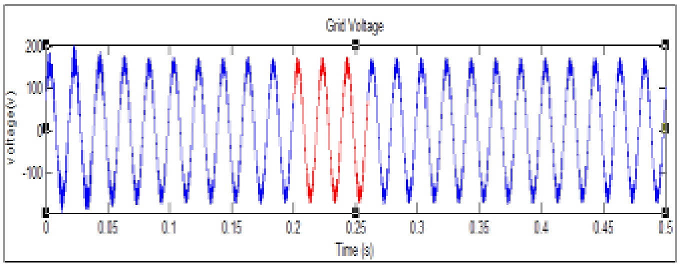

Figure 5: Grid voltage without compensator

6.2 Harmonic Profile

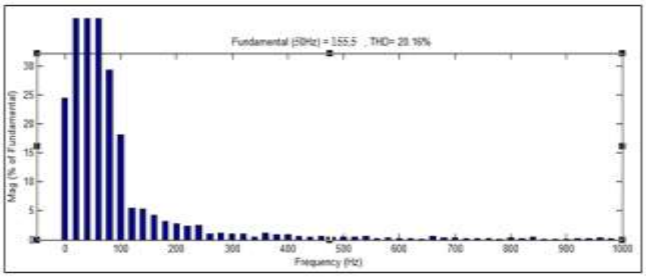

Figure 6: Harmonic profile without compensator

6.3 Grid voltage with lead lag compensator

This grid output voltage is taken when the inverter is connected to LCL filter and lead lag compensator across grid. The LCL filer improves the harmonic profile by reducing high order harmonics where lead lag compensator reduces low order harmonics and reduced the total harmonic distortion as 1.00%.

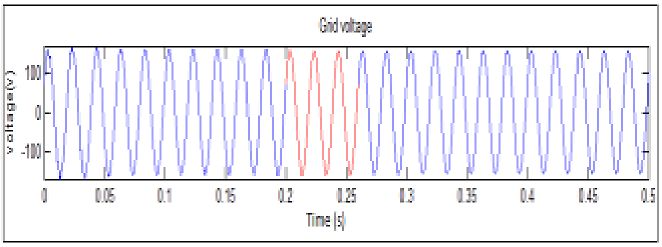

Figure 7: Grid voltage with lead lag compensator

6.4 Harmonic profile

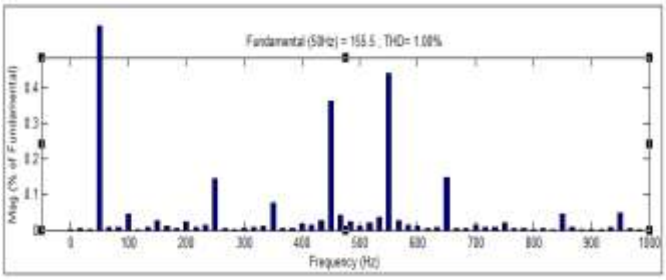

Figure 8: Harmonic profile with lead lag compensator

As observed from above results, the total harmonic distortion after using lead lag compensator is reduced from 20.16% to 1.00% for a three phase inverter output voltage. Where, Z-source inverter boosts the input voltage. From this we can conclude that lead compensator improves harmonic profile.

7. Conclusion

The injection of harmonic content in the grid side current is reduced by different harmonic compensating techniques. The selective harmonic compensation is carried out in grid-connected photovoltaic inverters by means of resonant harmonic compensators is accomplished. In this paper, a harmonic compensator that is Lead lag compensator is considered. The lead lag compensator is used to achieve the desired transient response and stability that improves harmonic profile than using lag compensator since it improve only steady state error. The Simulation for the grid connected Z-source inverter with LCL filter which reduces low order harmonics and with Lead lag compensator which reduces high order harmonics are carried out and their stability is also analyzed and it is observed that addition of Lead lag compensator improves harmonic profile and provides proper damping. A design of grid connected photovoltaic inverter meeting the requirements of grid interconnection using MATLAB Simulink and selected experimental results are also reported.

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