AN LLCL POWER FILTER FOR SINGLE-STAGE SINGLE PHASE GRID-TIED PV INVERTER

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***ABSTRACT*:** *This paper focuses on high performance control strategies of single-stage inverter for grid connected PV systems with a new topology of higher order power filter, named the LLCL filter. The proposed configuration can not only boost the usually low photovoltaic (PV) array voltage, but can also convert the solar dc power into high quality ac power for feeding into the grid, while tracking the maximum power from the PV array. The cost and efficiency of a photovoltaic (PV)-based grid-connected system depends upon the number of components and stages involved in the power conversion. When the controlled inverter is connected to the grid, the phase error results in a power factor decrement and the limited disturbance rejection capability leads to the need of grid feed-forward compensation. However the imperfect compensation action of the feed-forward control results in high harmonic distortion of the current and consequently non-compliance with international standards, to mitigate these drawbacks a new topology of higher order power filter for grid-tied voltage-source inverters, named the LLCL filter, which inserts a small inductor in the branch loop of the capacitor in the traditional LCL filter to compose a series resonant circuit at the switching frequency.*

KEYWORDS— Efficiency, grid-connected, inverter, photovoltaic (PV), single-stage, maximum power point tracking, perturbation and observation algorithm, PLL, Power filters

1. INTRODUCTION

Due to the latest developments in power and digital electronics, the market for small distributed power generation systems like photovoltaic (PV) systems connected to the domestic grid is increasing rapidly.

High initial investment and limited life span of a photovoltaic (PV) array makes it necessary for the user to extract maximum power from the PV system. The nonlinear i–v characteristics of the PV array [1] and the rotation and revolution of the earth around the sun, further necessitate the application of maximum power point tracking (MPPT) [2] to the system. Though, multistage systems [1] have been reported for certain applications, grid connected PV systems usually employ two stages [Fig. 1(a)] [3]–[4] to appropriately condition the available solar power for feeding into the grid. While the first stage is used to boost the PV array voltage and track the maximum solar power, the second stage inverts this dc power into high quality ac power. Typically, the first stage comprises of a boost or buck-boost type dc–dc converter topology.

Configurations are time tested and work well, but have drawbacks such as higher part count, lower efficiency, lower reliability, higher cost and larger size. The question is whether it is possible to reduce the number of power processing stages in such systems or, in short, is it possible to realize the situation depicted in Fig. 1(b)? Two simple and straightforward solutions to this requirement could be as follows.

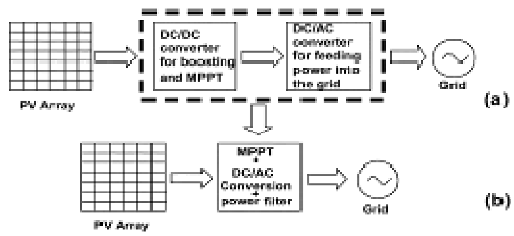


Figure 1 Grid connected PV system topologies: (a) Conventional two-stage and (b) single-stage configuration

1) Using the conventional H-bridge inverter followed by a step-up transformer [5].

2) Using an array with sufficiently large PV voltage, which may be realized using a string of series connected modules followed by an H-bridge inverter [6], [7].

While these options are feasible, they suffer from the following drawbacks. Adding a transformer (corresponding to the grid frequency) will add to the bulk and cost of the system, besides adding losses. On the other hand, a PV array with large dc voltage suffers from drawbacks such as hot-spots during partial shading of the array, reduced safety and increased probability of leakage current through the parasitic capacitance between the panel and the system ground [8], [9]. Further, in both the options, the inverter must take care of the Maximum Power Point Tracking (MPPT).

Harmonics level is still a controversial issue for PV inverters. The IEEE 929 standard from 2000 allows a limit of 5% for the current total harmonic distortion (THD) factor with individual limits of 4% for each odd harmonic from 3rd to 9th and 2% for 11th to 15th while a recent draft of European IEC61727 suggests something similar.

These levels are far more stringent than other domestic appliances such as IEC61000-3-2 as PV systems are viewed as generation sources and so are subject to higher standards than load systems.

In view of the ongoing discussion, it is reasonable to conclude that the best option is to have only a single power electronic stage between the PV array and the grid to achieve all the functions—namely the electrical MPPT, inversion, power filters. [Fig. 1(b)] leading to a compact system.

A low-pass power filter is often inserted between a voltage-source inverter (VSI) and the grid to limit the excessive current harmonics.

The most common solution is to use a third-order *LC* filter instead of a first-order *L* filter [7]. Compared with the first order *L* filter, the *LC* filter can meet the grid interconnection standards with significantly smaller size and cost, especially for applications above several kilowatts, but it might be more difficult to keep the system stable [8]–[10]. Moreover, selecting the parameters of an *LC* filter is also a more complicated process in contrast to an *L* filter [11], [12].

Sometimes, it is difficult to balance the factors of output current ripple sourced by insulated gate bipolar transistor switches, fundamental voltage drop, volt ampere reactive limits, and the resonance frequency.

An alternative solution in order to alleviate the LC filter drawbacks, given above, we highlighted comparative analysis of high-order filter, named the LLCL filter.

Simulation of modern electrical systems using power electronics has always been a challenge because of the nonlinear behavior of power switches, their connection to continuous sub-systems and the design of discrete-time control [12].Nowadays, more and more complex systems are studied for designing efficient control strategies, such as renewable energy conversion systems [13], whole traction systems [14] and so on. In these cases efficient simulations before practical control implantation are required.

2. SYSTEM DESCRIPTION

Usually the power converter interface from the dc source to the load and/or to the grid consists of a two stage converter: the dc-dc converter and the dc-ac converter.

An interesting alternative solution could be the use of a single-stage converter where the dc-dc converter is avoided and in order to ensure the necessary dc voltage level the PV array can be a string of PV panels or a multitude of parallel strings of PV panels. In the classical solution with two-stage converter, the dc-dc converter requires several additional devices producing a large amount of conduction losses, sluggish transient response and high cost while the advantages of the single-stage converters are: good efficiency, a lower price and easier implementation. The disadvantages of the single-stage converter are the fact that the PV panels are in series and if the shading occurs on one or several PV panels then the efficiency of the whole system is reduced [15].

3. CONTOL STATERGY

For the grid-connected PV inverters, the most common control structure for the dc-ac grid converter is a current-controlled H-bridge PWM inverter having a output power filters. Typically L and LCL filters are used but we can also use LLCL, LC and OTT filters that have a higher order (3rd), which leads to more compact design. [16].

The control structure of the PV energy conversion system is shown in Fig.2. The main elements of the control structure are the synchronization algorithm based on PLL, the MPPT, power filters and the grid current controller.

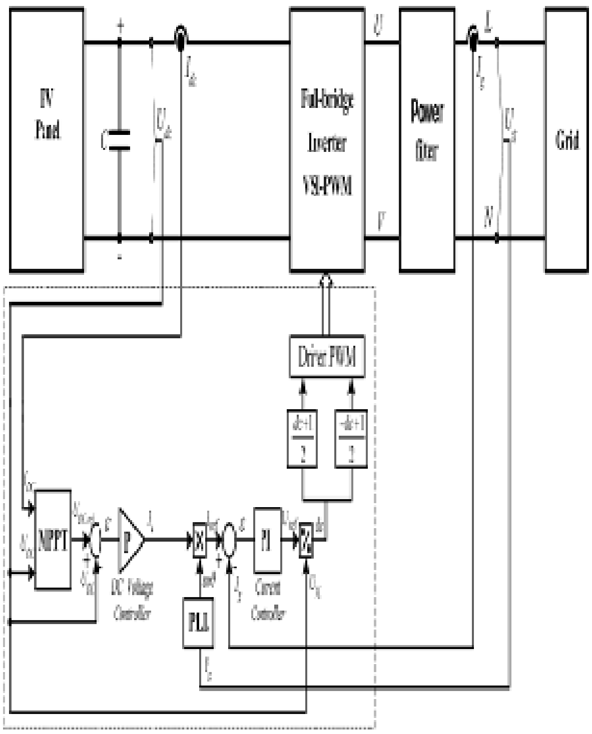


Figure 2 Control diagram

4. MPPT ALGORITHAM

The task of the MPPT in a PV energy conversion system is to tune continuously the system so that it draws maximum power from the solar array regardless of weather or load conditions. Since the solar array has non ideal voltage-current characteristics and the conditions such as irradiance, ambient temperature, and wind that affect the output of the solar array are unpredictable, the tracker should deal with a nonlinear and time-varying system.

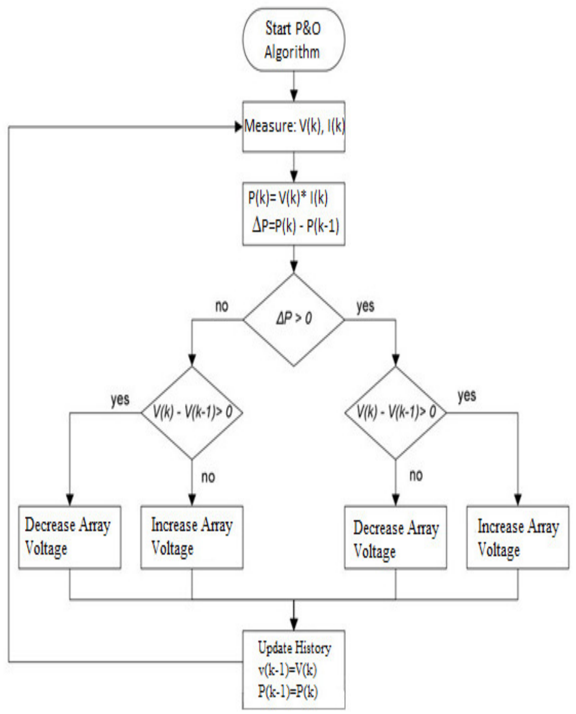


Figure 3 Flowchart of Perturb & Observe algorithm

5. PLL STRUCTURE

The PLL is used to provide a unity power factor operation which involves synchronization of the inverter output current with the grid voltage and to give a clean sinusoidal current reference. The PI controller parameters of the PLL structure are calculated in such a way that we can set directly the settling time and the damping factor of this PLL structure. The PLL structure is also used for grid voltage monitoring in order to get the amplitude and the frequency values of the grid voltage.

6. PARAMETER DESIGN OF THE LLCL FILTER

A. Constraints and Procedure on the Power Filter Design.

When designing the power filters (whether it is an LCL or LLCL filter), some limits on the parameter values should be introduced.

1) The capacitor value Cf is limited to the decrease of the capacitive reactive power at rated load to less than 5%.

2) The upper limit to the total inductance (L1 + L2) depends on the voltage drop during operation (lower than 10%).

3) The value of the inverter-side inductor L1 is limited to the requirement of the ripple current (generally lower than 40%).

4) IEEE 519-1992 recommends that harmonics higher than the 35th should be limited. For a grid-tied inverter system, if the short-circuit current of power system is lower than 20 times the nominal grid-side fundamental current, then each harmonic current of higher than the 35th should be less than 0.3% of the rated fundamental current.

5) The resonance frequency fr or ωr should be in a range between ten times the line frequency and one half of the switching frequency in order to not create resonance problems in the lower and higher parts of the harmonic spectrum.

7. SIMULATION RESULT

A single-stage grid-connected PV inverter (60w power range) was built in order to analyze the PV systems performance. The system is MATLAB based and voltage source inverter (VSI) is controlled using a unipolar PWM to place the harmonics on the high frequency side making them easier to filter. The parameters of the various power filters are shown in table below:

PARAMETERS	LC FILTER	LLCL FILTER
L1	2.5mH	0.1mH
R1	0.1Ω	0.1Ω
L2	-	1.2mH
R2	-	0.1Ω
LF	-	2nH
RF	-	0.1Ω
CF	2uF	15uf

The system was tested in the following condition: - the open circuit dc voltage provided by the single PV panel was around 16V, the grid impedance was measured to 0.3Ω with a series inductance of 0.7 mH. The switching frequency of the inverter is 10 kHz.

The Solarex MSX60, a typical 60W PV module, was chosen for modeling. The module has 36 series connected polycrystalline cells. The key specifications are shown below:

At Temperature T	=25 C
Open Ckt Voltage VOC	=21.0 V
Short Ckt Current ISC	=3.74 A
Voltage, max power Vm	=17.1 V
Current, max power Im	=3.5 A
Maximum Power Pm	=59.9 W

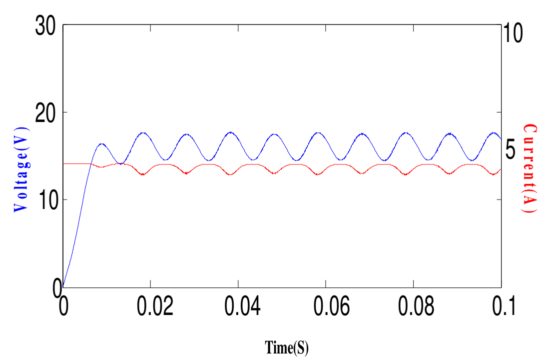
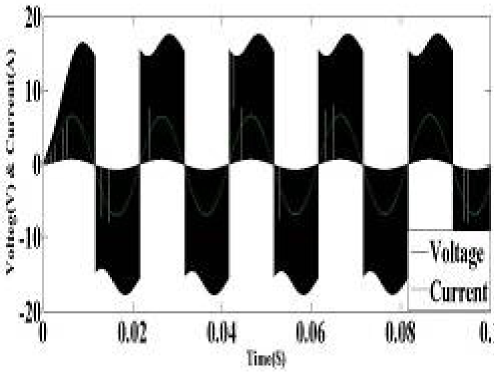
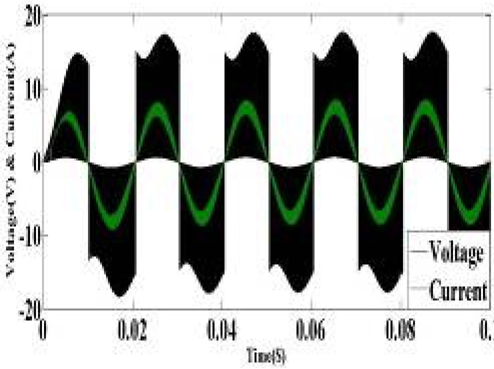


Figure 4 PV module Voltage & Current

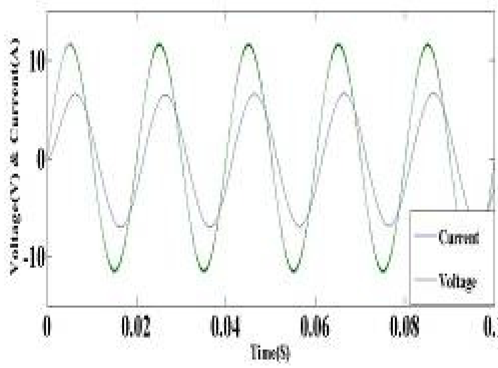


(a)

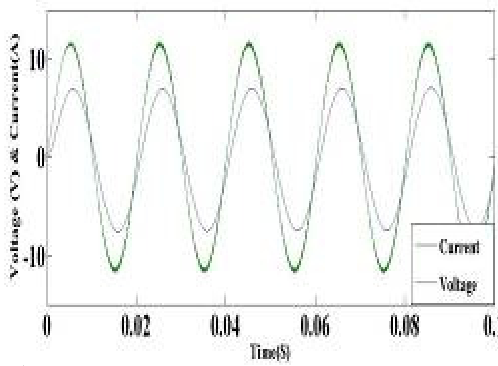


(b)

Figure 5 Inverter voltage and current using Simulink model (a) LC filter (b) LLCL filter



(c)



(d)

Figure 6 Grid voltage and current using Simulink model (c) LC filter (d) LLCL filter

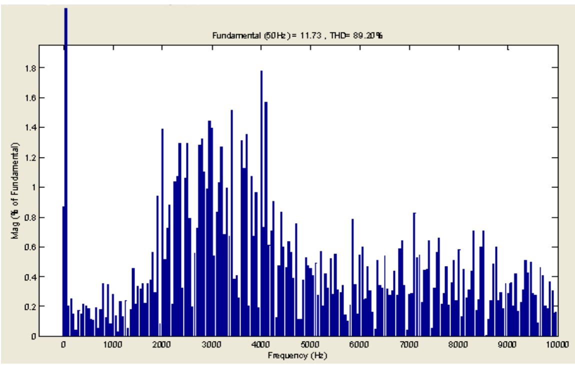


Figure 7 Measured grid voltage harmonic spectrum without filter

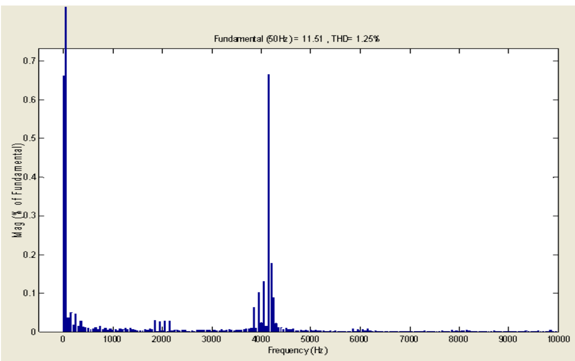


Figure 8 Measured grid voltage harmonic spectrum with LLCL filter

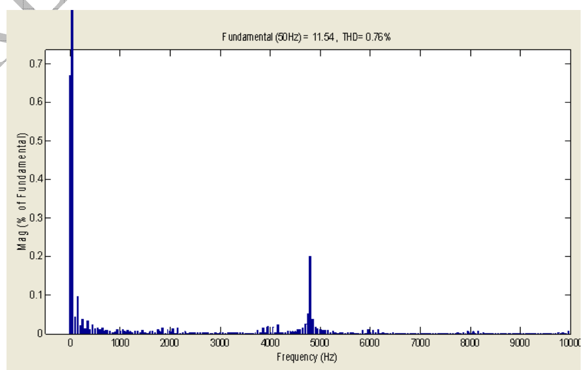


Figure 9 Measured grid voltage harmonic spectrum with LC filter

The grid current and grid voltage for PI, controller is presented in table below, for various power filters.

Power Filter	Ug (V)	Ig (A)	THD (V)%	THD (I)%	POWER FACTOR
LC	11.51	6.5	0.76	0.33	0.9567
LLCL	11.54	6.5	1.25	0.39	0.9734

Harmonic comparison with various filters:

Freq	Harmonic No.	W/O FILTER THD	LLCL FILTER	LC FILTER
0	DC	0.59%	0.66%	0.67%
50	Fnd	100%	100%	100%
100	h2	0.11%	0.03%	0.04%
150	h3	0.40%	0.06%	0.10%
200	h4	0.22%	0.01%	0.02%
250	h5	0.39%	0.04%	0.04%
300	h6	0.21%	0.01%	0.01%
350	h7	0.19%	0.03%	0.03%
400	h8	0.10%	0.01%	0.01%
450	h9	0.35%	0.01%	0.02%
500	h10	0.06%	0.01%	0.01%
550	h11	0.17%	0%	0.01%
600	h12	0.13%	0%	0.01%
650	h13	0.43%	0.01%	0.01%
700	h14	0.25%	0.01%	0.01%
750	h15	0.05%	0.01%	0.01%
800	h16	0.38%	0%	0.01%
850	h17	0.21%	0.01%	0%
900	h18	0.46%	0%	0.01%
950	h19	0.17%	0.01%	0.01%
1000	h20	0.33%	0%	0.01%
1050	h21	0.15%	0%	0.01%
1100	h22	0.08%	0%	0.01%
1150	h23	0.30%	0.01%	0.01%
1200	h24	0.18%	0%	0.01%
1250	h25	0.32%	0.01%	0%
1300	h26	0.20%	0.01%	0.01%
1350	h27	0.26%	0.01%	0.01%
1400	h28	0.16%	0.01%	0%
1450	h29	0.20%	0%	0.01%
1500	h30	0.06%	0%	0%

8. CONCLUSION

A high performance single-stage inverter topology for the single phase of photovoltaic system with the simple closed loop control scheme is highlighted. Further, adoption of a simple control strategy makes the inverter more reliable. The cost of this inverter will also be relatively low as less number of power devices is used to execute this configuration. A 60W-single-phase grid-tied inverter is used to compare the characteristics of the conventional LC and LLCL filter through simulation results.

It can be seen that without filter the main high-order harmonic mostly appear around the switching frequency. Based on this, a various topologies of low-pass power filters have been highlighted.

The LC filter has low fundamental value and lower power factor compare to other power filters. The LLCL filter has nearly zero impedance at the switching frequency and can strongly attenuate the harmonic around the switching frequency. Power factor can be also improved with LLCL filter.

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