# Solar Inverter Synchronization with the Electrical Grid

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## ABSTRACT

This Master thesis presents a single phase grid connected DC/AC inverter with active and reactive power (VAR) control for medium size renewable and distributed DC energy sources. The inverter, based on a voltage sourced inverter (VSI) configuration, allows the local residential energy generation to actively supply reactive power to the utility grid, at the same time, this topology allows to work this installation in stand-alone (grid disconnected) mode maintaining nominal and clean voltage at nominal power. A low complexity grid synchronization method was introduced to generate direct and quadrature components of the grid voltage in a simple and computationally efficient manner in order to generate a synchronized current reference for the current loop control. The main goal of this project is to study and to implement the control system of a grid-tied with LCL filter. The objectives of the project are divided in two parts: theoretical and experimental work. In the theoretical part, harmonics, inverter topologies, filter topologies, the design and the performance of the system will be discussed. Simulations were performed on Matlab/Simulink platform and a prototype was also developed in the lab to prove the effectiveness of the designed filter, controllers and grid synchronization method. The hardware in the loop (HIL) was used, providing a good solution for laboratory implementation.

**Keywords –** *VAR, VSI, LCL filter, Matlab/Simulink, HIL, etc.*

## 1. INTRODUCTION

When a power converter is in grid-tied mode, the injected power quality must comply with interconnection standards, which becomes a design concern with inverter - grid interface design as well as a controller design specification. The most common power converter is the voltage-source- inverter (VSI) which produced a modulated output voltage that must be filtered in order to parallelize a voltage output with the utility voltage grid. The most common type of filter is a pure inductance (L), which serves as an impedance for absorbing the voltage variation. Although a LC filter could potentially be used with transformer based interconnection (since the transformer has leakage inductance), the most recommended filter has a LCL (inductor-capacitor-inductor) topology. LCL filters seem to be a good solution for this problem, since they offer a higher harmonic attenuation with reduced power consumption. even with smaller inductances when compared to simple L filters. The grid presents an unknown grid impedance which may cause instability by the dramatic changes of the resonant frequency in grid tie mode with an LC filter. There are different approaches to design LCL filter. Some authors propose iterative solution for parameters calculation and optimization using sophisticated algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithm (GA. However it has been observed that there is a gap in the analysis and evaluation of the LCL filter for systematic design methodology. So the comprehensive and detailed design procedure for the LCL filter and stability of the overall system will be provided.

The control strategy applied to the stand-alone and grid connected inverter usually consists of two cascaded loops, i.e. a fast internal current loop, which regulates the grid active and reactive current, and an external voltage loop, which controls DC link voltage. 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. Some authors propose a grid-side control based on the fact that the dc-link voltage loop can be cascaded with an inner power loop instead of a current loop, so the current is not controlled directly

## 2. MATHEMATICAL AND ENGINEERING ANALYSIS

This Section presents the inverter control design, with optimized LCL output filtering and grid synchronization through a PLL. Initially, the PLL is described and feeds the signals for the current loop, which is implemented based on a proportional-integral (PI) controller, capable of running in both stand- alone and grid-connected modes. The last section of this chapter shows the design procedure for a LCL filter, emphasizing their performance analysis based on rigorous mathematical modeling. The block diagram of the inverter control considered in this project is shown on Figure 2.1

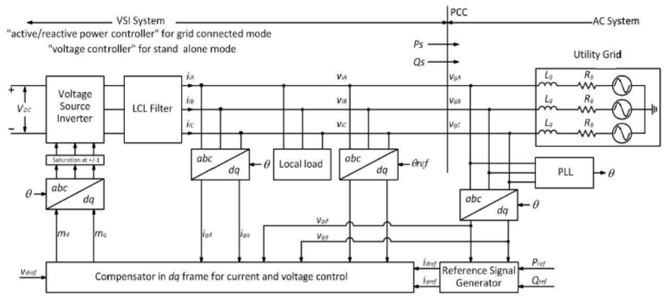


**Figure 2.1. Block diagram of the single phase inverter control system.**

The current is oriented along the active voltage component ($V_d$), this is why this strategy is called voltage oriented control. A PLL algorithm detects the phase angle of the grid, the grid frequency and the grid voltage. The frequency and voltage are needed for monitoring the grid conditions and for dynamic stability of the system. The phase angle of the grid is required for reference frame transformations (see Appendix A). If a PI current control is implemented, then the currents are transformed into the synchronous reference frame, and the algorithm also implements the decoupling between the two axes**.**

### 2.1 PLL Theory

The PLL block models a Phase Lock Loop (PLL) closed-loop control system, which tracks the frequency and phase of a sinusoidal signal by using an internal frequency oscillator. The control system adjusts the internal oscillator frequency to keep the phases difference to 0. The figure shows the internal diagram of the PLL.

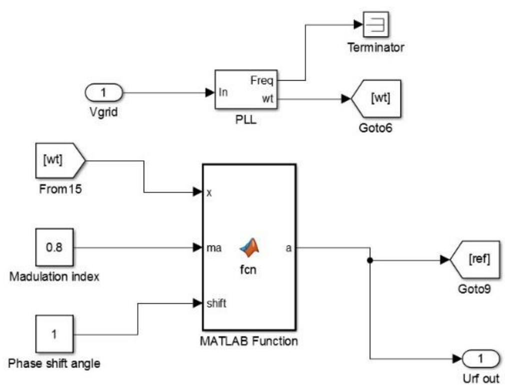


**Figure 2.2 PLL block diagram.**

The input signal is mixed with an internal oscillator signal. The DC component of the mixed signal (proportional to the phase difference between these two signals) is extracted with a variable frequency mean value. A Proportional-Integral-Derivative (PID) controller with an optional automatic gain control (AGC) keeps the phase difference to 0 by acting on a controlled oscillator. The PID output, corresponding to the angular velocity, is filtered and converted to the frequency, in hertz, which is used by the mean value.

## 3. SIMULATION STUDIES

This section shows different scenarios that have been studied in order to support a simulation based design of an inverter system capable to operate in stand-alone and in grid-connected modes using Matlab/Simulink platform. It is composed of four sections: the first and second ones contain case studies that support the control design and the LCL filter simulation performance evaluations for the standalone mode and grid connected mode operation. The third part contains simulation for ride-through operation, and the system response when the inverter transits to standalone from grid connected mode. The last section contains further results evaluation and discussions.

### 3.1 Stand Alone Mode Operation

The block diagram of the simulated system is shown on Figure 3.1. The system was built using Power Systems Toolbox in Simulink. The total harmonic distortion (THD) analysis was done with Power Systems Toolbox. Figure 3.2 shows a voltage closed loop controller block diagram that was implemented for the inverter.

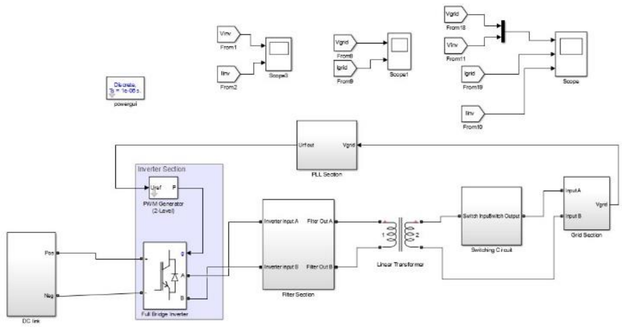

**Figure 3.1 Simulink model of stand-alone inverter with load.**

### 3.2 Grid Connected Mode

When the inverter is connected to the grid, capable of providing active and reactive power the system must behave in current-controlled mode. Many case studies have been considered for active power injection to the grid, mixed power injection and also when the inverter takes power from the grid (for example in charging a battery in the dc-link). All those cases have been thoroughly simulated in order to observe system behavior and performance.

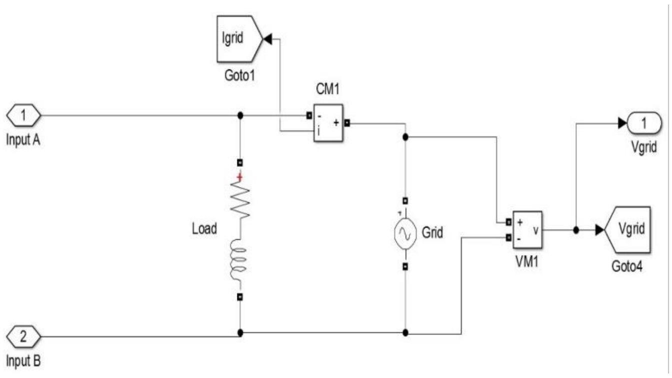


**Figure 3.2 Simulink model of grid connected inverter.**

### 3.3 Power Injection to the Grid

The DC Voltage Source block implements an ideal DC voltage source. The positive terminal is represented by a plus sign on one port. You can modify the voltage at any time during the simulation.

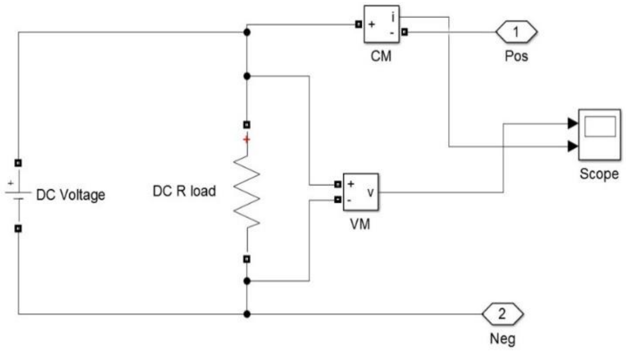


**Figure 3.3 DC voltage source.**

The DC Voltage Source block represents an ideal voltage source that is powerful enough to maintain specified voltage at its output regardless of the current flowing through the source. You specify the output voltage by using the Constant voltage parameter, which can be positive or negative. Connections + and – are conserving electrical ports corresponding to the positive and negative terminals of the voltage source, respectively. The current is positive if it flows from positive to negative, and the voltage across the source is equal to the difference between the voltage at the positive and the negative terminal, V(+) – V(–).Output voltage. You can specify positive or negative values. The default value is 1 V.

## 4. EXPERIMENTAL SETUP

This section describes the simulation model used for the experimental evaluation of the inverter system. The system setup comprised of a hardware-in-the-loop (HIL) that allowed all the Simulink based solution that allowed a fair comparison of simulation and experimental results.. The components include a inverter, a source of DC power supply, a LCL filter, switching circuit circuits, current and voltage measurement to providing voltage and current feedback, pll and pwm generator.

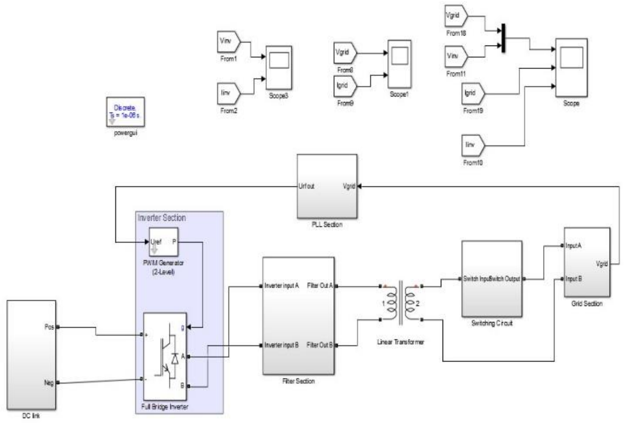

**Figure 4.1 Complete experimental setup.**

The single-phase inverter injects active power into the grid and compensates the harmonics generated by a local load, which contains two parts: a 2-kW linear load and a 3-kVA nonlinear capacitive load (a single-phase diode rectifier with capacitive dc load). The linear load (Z2) has been considered in the experimental tests either as a single resistance (R2) or as a series RL load (R2 , L2 ), whose values are specified in Table I.

**Table No. I EXPERIMENTAL SETUP PARAMETERS**

| Parameter | Symbol | Value |
|---|---|---|
| Mains voltage | $v_S$ | 220 V |
| Interface capacitance | $C_F$ | 7.5 μF |
| Interface inductance | $L_F$ | 700 μH |
| DC-link capacitance | $C_d$ | 2.2 mF |
| DC-link voltage setpoint | $V_{dc}$ | 400 V |
| Switching/Sampling frequency | $f_{sw}, f_s$ | 10 kHz |
| Fundamental frequency | $f_1$ | 50 Hz |
| Linear load resistance | $R_2$ | 25 Ω |
| Linear load inductance | $L_2$ | 30 mH |
| Nonlinear load input inductance | $L_1$ | 900 μH |
| Nonlinear load output capacitance | $C_1$ | 1 mF |
| Nonlinear load output resistance | $R_1$ | 50 Ω |

## 5. EXPERIMENTAL RESULT

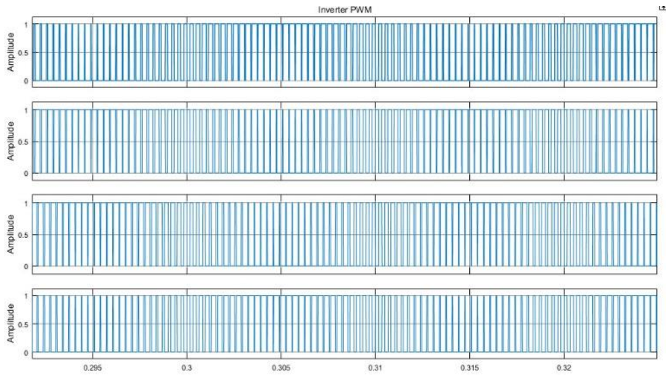


**Figure 5.1 PWM Pulses**

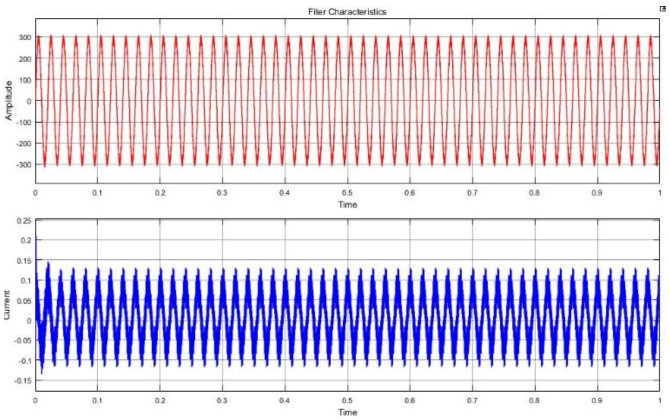


**Figure 5.2 Filter Output**

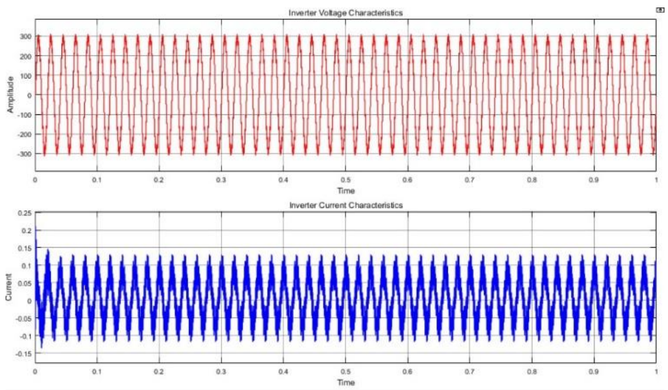


**Figure 5.3 Inverter Output**

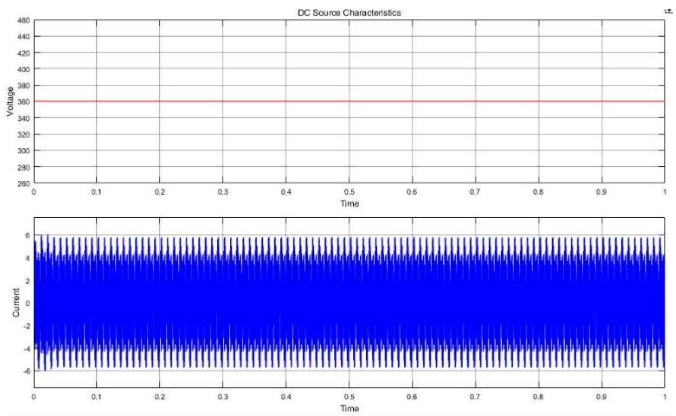


**Figure 5.4 DC Source Output**

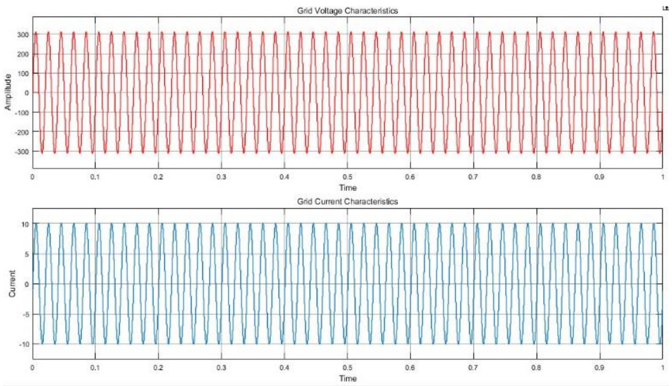


**Figure 5.5 Grid Output**

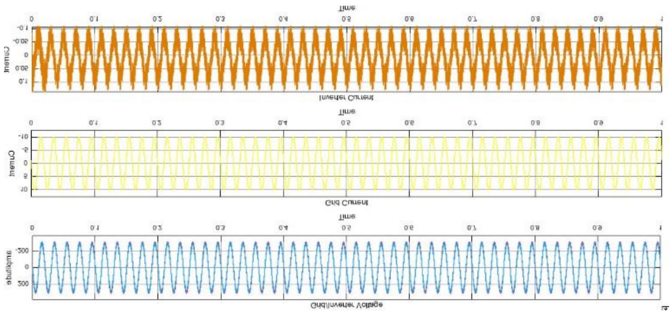

**Figure 5.6 Grid Inverter Output**

## 6. Advantages

- **Benefits of Grid Synchronization**

Grid synchronization provides numerous benefits for solar power addition. It enhances grid stability, renewable energy addition, and improves cost savings and grid efficiency. Moreover, supports the implementation of smart grid technologies.

- **Enhanced grid stability and reliability**

Grid synchronization plays a crucial role in enhancing grid stability and reliability when it comes to solar inverters. Solar inverters makes sure that there is a smooth addition of renewable energy into the electric grid. This is done by synchronizing the frequency, phase, and amplitude of voltage with the utility grid.

This synchronization allows for smooth power flow between the solar PV system and the grid. Thus, reducing disruptions and enabling efficient utilization of clean energy. The synchronized operation also helps maintain stable voltages and frequencies within acceptable limits, and reliable power supply to consumers.

- **Renewable energy addition**

Grid synchronization for solar inverters allows the addition of renewable energy into the electrical grid. As solar power becomes more widely adopted, it plays a vital role in reducing reliance on fossil fuels. Solar inverters are able to feed excess electricity generated by photovoltaic panels back into the system. Thus, effectively adding to the overall power output.

This means individual households or any form of business to generate their own renewable energy. They can also contribute to boosting clean energy production at a larger scale.

- **Cost savings and grid efficiency**

Grid synchronization of solar inverters brings environmental benefits, cost savings, and improved efficiency to the electrical grid. By adding solar power into the grid, there is a reduction in reliance on fossil fuel-based energy sources. This can help lower electricity costs for consumers.

Additionally, grid-tied inverters allow for efficient load sharing between the solar system and the grid, optimizing power distribution. This helps to reduce strain on the grid during peak demand periods while utilizing excess solar energy when available.

With more renewable energy addition through synchronized inverters, utilities can have a more balanced and stable grid operation. Basically, leading to overall cost savings and improved power generation and distribution efficiency.

- **Support for smart grid technologies**

In addition to enhancing grid stability and reliability, grid synchronization also opens up opportunities for supporting smart grid technologies. Smart energy management systems can efficiently monitor and control the flow of electricity.

This enables utilities to better manage power distribution, implement demand response programs, and optimize overall energy consumption. With synchronized solar inverters, homeowners and business owners can actively participate in shaping a sustainable energy future. This is by returning their excess solar power to the grid during peak times or when it is most needed.

## 7. LIMITATIONS

- The solar radian flux availability is a low value 1 kW / $m^2$ for technological utilization.
- Large collecting area required and Cost is more.
- Availability varies with time.
- In many applications, energy storage is required at night.
- The relatively poor conversion efficiency.

## 8. CONCLUSION and FUTURE SCOPE

### 8.1 Conclusion

This paper deals with a single-phase H-bridge inverter for DG systems, requiring power quality features as harmonic and reactive power compensation for grid-connected operation. The proposed control scheme employs a current reference generator based on SSI and IRP theory, together with a dedicated repetitive current controller. The grid-connected single-phase H-bridge inverter injects active power into the grid and is able to compensate the local load reactive power and also the local load current harmonics.

Experimental results have been obtained on a 4-kVA inverter prototype tested for different operating conditions, including active power generation, load reactive power compensation, and load current harmonic compensation. The experimental results have shown good transient and steady state performance in terms of grid current THD and transient response.

The integration of power quality features has the drawback that the inverter will also deliver the harmonic compensation current with the direct consequence of increase the inverter overall current and cost. A current limitation strategy should be implemented and if the inverter output current exceeds the switch rating, then the supplied harmonic current must be reduced. In this way, the inverter available current is mainly used for active power injection and if there is some current margin, this can be used for the compensation of reactive power and nonlinear load current harmonics. An analysis of the inverter design that takes into account the current required for reactive power and current harmonics compensation is beyond the paper scope and it will be subject of future study.

### 8.2 Future Scope

Design and implementation of other control strategies for the grid side converter in order to do a comparison between methods of control. Advanced relay protection of inverter, which will be done in hardware and independently from computer with control system; Evaluation of virtual resonance damping technique in LCL filter for real implementation. Grid connected control system optimization with weak grid operation(independent operation of inverter from grid conditions). Incorporating a storage system in order to provide power for critical load under black out and no sun condition. Implementing an energy-management system to minimized the operation cost and enhance the system stability. Grid fault ride through. Real time communication implementation between control system and utility grid. An advanced voltage control system with nested current loop for stand-alone operation.

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