PI-based PLL and 24-sector control of a 3P-3L-NPC inverter for grid-tied PV system synchronization

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ABSTRACT

This article addresses one of the most serious issues in electricity: frequency and voltage anomalies. Actually, because renewable energy production is intermittent, the frequency and voltage of electricity produced are unstable and dependent on weather conditions. This issue causes industrial processes to fail, affecting the quality of the electrical supply and having a massive economic impact. Power electronics inverters are designed to compensate for system fluctuations in solar power generation. However, measurement noise in the grid voltage desynchronizes the inverter and network signals. The authors propose using a phase-locked loop technique based on inverter period control and a network voltage observer to achieve such synchronization of grid-connected photovoltaic (PV) systems. In this work, the grid integration of the PV system is carried out through a three-phase three-level neutral point clamped inverter due to better current quality with fewer harmonics and lower stress voltage of the inverter's components when compared to two-level voltage source inverters. The method is successfully applied in a simulated case study and experimental results validate it.

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1. INTRODUCTION

Among the various renewable energy sources, solar energy is a compelling alternative solution that is extremely environmentally friendly. The intermittent nature of solar photovoltaic, on the other hand, complicates controllability and causes grid stability issues. Ahmed *et al*. [1] and Schmietendorf *et al*. [2] present the three major challenges that conventional grids face when adopting renewable energy sources. The first is overburdening existing transmission lines. It can happen when producers generate too much power without warning, and a transmission line has a specified capacity; if this limit is exceeded, thermal loads build up, causing damage. The second issue is a mismatch between demand and supply. It is possible that under certain meteorological conditions, the power generated will not be available when needed. The last issue which affects seriously the grid stability is the frequency and voltage anomalies.

Auer *et al*. [3] and Anvari *et al*. [4] have argued that power electronics inverters are used to correct system fluctuations in solar power generation. However, measurement noise in grid voltage causes a desynchronization of inverter and network signals. According to Wu and Wang [5], because of its simplicity, the phase-locked-loop can be considered as the mainly used technique to avoid this problem of desynchronization in grid-tied PV system via power inverter.

Several grid synchronization schemes have been described, and comparative studies of a few of them have been conducted and published in [6]–[9]. A phase-locked loop is a common grid synchronization method. It is crucial in power generation systems that are linked to the grid. It is difficult to obtain accurate knowledge of the phase and frequency of grid voltage. As mentioned in [10], detecting the zero-crossing point of the network voltages is a simple method of obtaining phase information. However, because of the noisy voltage measurements, detecting the point is not always possible at every half-cycle of the utility frequency. Agamy *et al*. [11] proposes a synchronization circuits connecting wind driven direct field induction generator to the public grid.

Another technique employs a 90-degree shift in the quadrature of the input waveform. This approach is frequently used in various applications for detecting phase or angular position, and it has been adopted by [12] for electric motor speed control. A new PLL method for single phase systems is proposed in [13]. The novelty in this reference is to generate an orthogonal voltage system using a second order generalized integrator (SOGI), followed by a park transformation, whose quadrature component is forced to zero by the fuzzy logic, in order to obtain rapid detection and a more accurate picture of the phase angle. There are additional requirements for three-phase applications, such as estimations of the fundamental positive or negative sequences, which are typically used in the flexible power control of grid-interfaced converters for distributed power generation [14] and active power filters [15] under distorted and unbalanced conditions. The three-phase PLL discussed by Escobar *et al*. [16], employs a synchronous reference frame to identify the phase angle, frequency, and amplitude of the three phase grid voltages.

In this work, the authors propose a phase-locked loop (PLL) technique using the inverter period adjustment and the grid voltage observer. It is mainly based on an estimation of modular period after verification of the network and the inverter angular positions. To control this inverter, a modified number of voltage sectors is proposed. Surprisingly, it was found that using 24 sectors instead of 12 or 6 sectors was unexpectedly possible. This clever solution is applied to the three phase three level neutral point clamped (3P-3L-NPC) inverter, which can be used as a bridge between the PV source and the grid. This paper is organized as follows: Section 2 describes major photovoltaic system components, including the power inverter. Section 3 proposes a PLL method to synchronize the inverter and the grid voltages. Section 4 shows simulation and practical verification results. Finally, section 5 concludes the paper.

2. MAJOR PHOTOVOLTAIC SYSTEM COMPONENTS

PV modules, as shown in Figure 1, are the most important component of a photovoltaic system [17]; they capture daylight to produce electrical energy using the PV effect. Batteries are used to convert chemical energy to electrical energy in a reversible manner. These electrochemical storage systems should have sufficient ability to pile up the energy generated in the day so that it can be used at night and during bad weather.

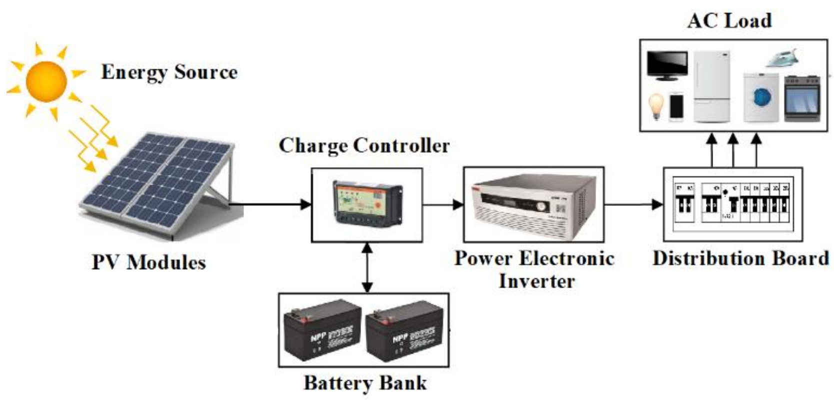


Figure 1. Major photovoltaic system components

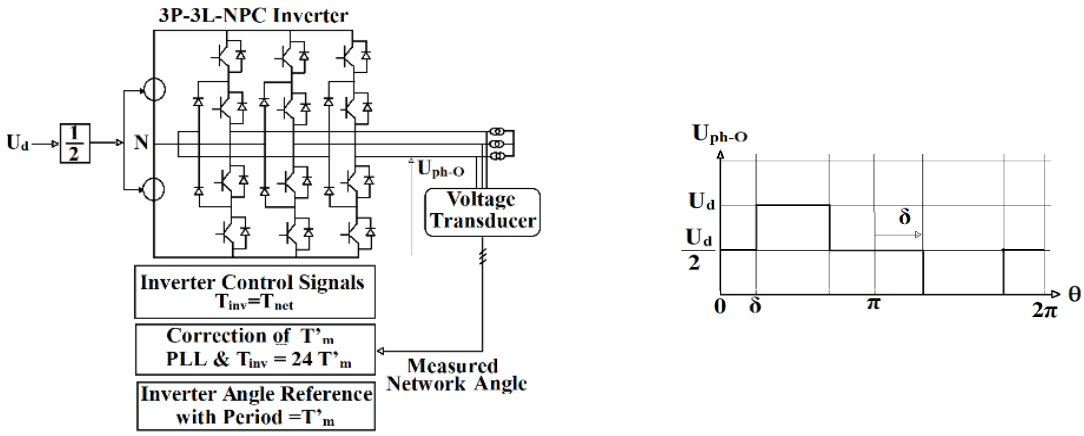
When the batteries are fully charged, a charge controller disconnects them from the PV modules and may detach the load to prevent the batteries since being discharged under a certain voltage. Furthermore, the charge controller includes DC-DC converters to ensure that the PV voltage and current are independent. The solar panel is directly connected to the power electronic inverter. It transforms the DC current generated by the PV array into an alternating current (AC) network at fifty or sixty hertz. The PLL technique must then be used to guarantee the inverter and network voltages synchronization [18].

3. METHOD

3.1. Power electronics inverters

Power electronics inverters of various topologies serve as an interface between the PV system and the grid. The grid integration of the PV system is carried out in this section using a three phase, three level neutral point clamped inverter [19]. Compared to two-level voltage source inverters, the use of the 3P-3L-NPC inverter is due to better current quality with fewer harmonics and lower stress voltage of the inverter's components. Furthermore, when a square wave modulation is used to control it, it has a high efficiency. As proved in [20], this mode has the benefit of having lower switching losses.

The proposed control strategy for the 3P-3L-NPC inverter is depicted schematically in Figure 2(a). The DC side, which is the charge controller's output, will be connected to the capacitor midpoint N via diodes in this configuration to provide the third level in the output waveform injected to the grid. The output voltage waveform of 3P-3L-NPC inverter operated on SWM shown in Figure 2(b) must have the same frequency as the grid voltage. As a result, the synchronization block is an essential component of the controller in grid power converters. The authors propose a network voltage observer to synchronize the inverter and grid signals.



(a) (b)

Figure 2. The proposed control strategy: (a) schematic diagram of 3P-3L-NPC inverter and (b) output voltage waveform of 3P-3L-NPC inverter operated on SWM

3.2. Network voltage observer

The proposed network voltage observer is depicted schematically in Figure 3. It is mainly based on an estimation of modular period after verification of the network and the inverter angular positions. The difference between the inverter angle reference and the network measured angle is used as input to a simple PI corrector in this structure. The adjusting time shown in the output is added to the sector period T_{m0} reference to keep the ratio between network and sector periods constant and thus achieve $T_{inv}=T_{net}$.

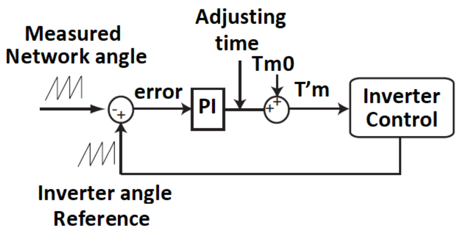


Figure 3. Schematic diagram of a network voltage observer.

3.3. Inverter control signals

The inverter reference angle is generated, as prsented in Figure 4, by a sinusoidal signal with an adjustable period T'_m. Figure 5 shows the decomposition of the inverter control signal into 24 sectors. The goal of this decomposition is to have more precision on T'_m, correct it instantly (as shown in Figure 3), and then keep $T_{inv}=24\times T'_m$ to synchronize the inverter and grid voltages.

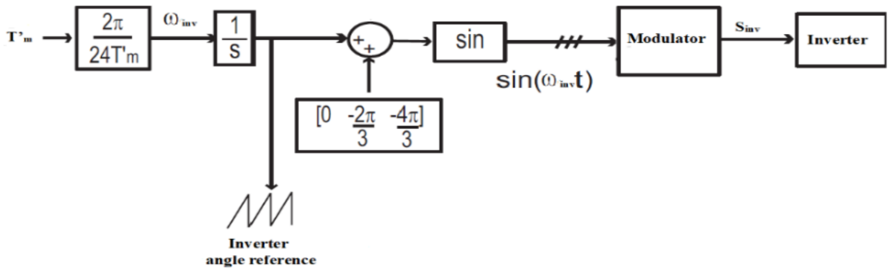


Figure 4. Schematic diagram of inverter angle generation.

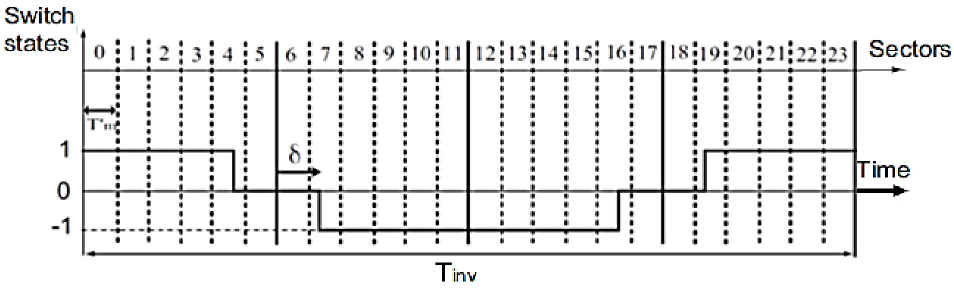


Figure 5. Decomposition into 24 sectors of the inverter control signal.

4. RESULTS AND DISCUSSION

The system depicted in Figure 2 was tested with MATLAB/Simulink and verified using a low-voltage laboratory prototype. The simulated and measured results are shown in Figure 6. The periods of the network and inverter angles are the same. This means that the voltages on the grid and the inverter are synchronized. The simulation results, which are supported by experimental measurements, show that the PLL technique presented in the previous sections is suitable.

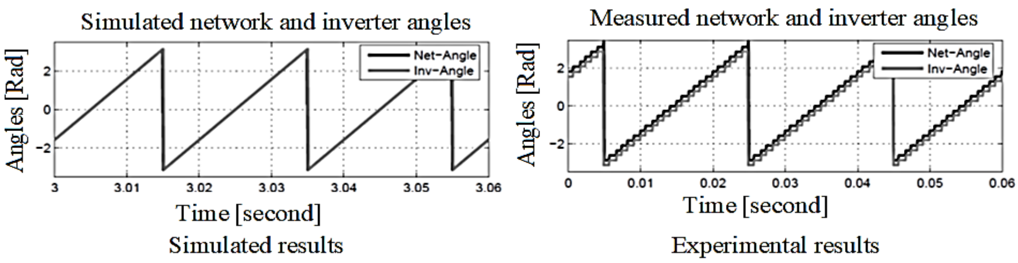


Figure 6. Simulated and measured angles.

Figure 7 plots the simulated active and reactive powers together with inverter and network voltages. The line current is also presented. Starting from the active and reactive power references, the system runs initially in no load operation, with active and reactive powers equal to zero. In the first transition at (t=0.6s), the network active and reactive powers are ramped from (P_{ref}=0 and Q_{ref}=0) to ($P_{ref}=S_n\times\cos\varphi$ and to $Q_{ref}=S_n\times\sin\varphi$) respectively Figure 7(a). Consequently, the inverter and network voltages don't have the same phase, the line current is different from zero and the system operates with ($\cos\varphi\neq1$) Figure 7(b). In the second transition, at (t=10s), the reactive power ramps down to zero, the inverter and network voltages have the same phase Figure 7(c). Then the reactive power can be compensated and the system can be operated using a unity power factor ($\cos\varphi=1$). On the other hand, as depicted in Figure 7(a), the transition of the active and reactive powers can be done in small and well-defined period, without generating the continuous component in the line current [21].

Figure 8(a) shows measured active and reactive powers when the system operates with unity power factor (cosφ=1). The alternative line current, inverter and network voltages are also presented in Figure 8(b). It is well shown that the alternative line current is in phase with the network voltage when the reactive power is near to zero. As these curves show, the correspondence between simulation and experimental results is satisfactory. Using a three phase, three level neutral point clamped inverter as an interface between the PV system and the grid allows to have a better current quality (see Figure 8(c)), with fewer harmonics and a lower stress voltage of the inverter's components compared to two level voltage source inverters.

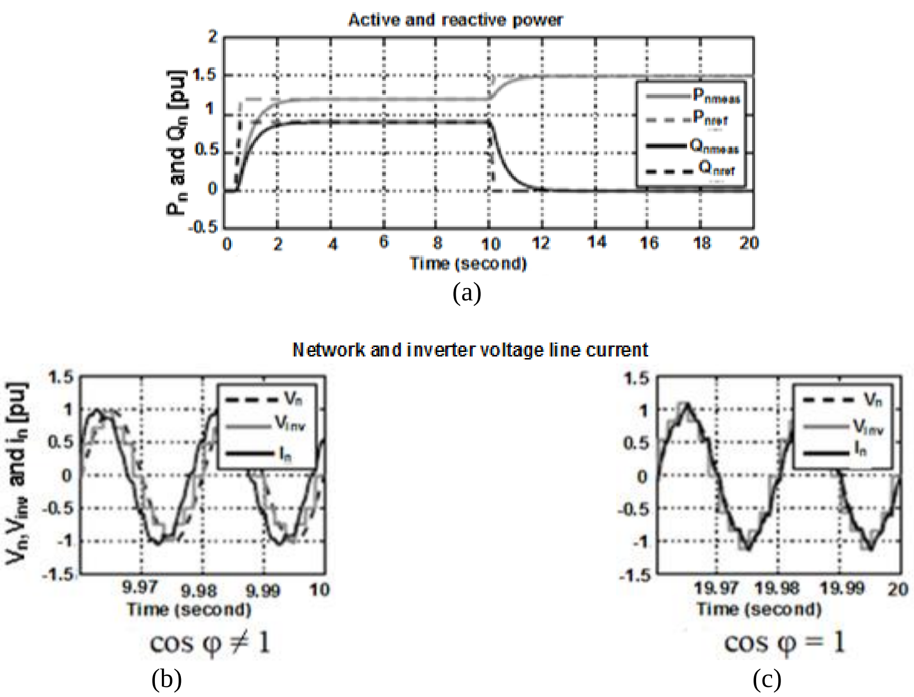


Figure 7. Simulated results: (a) powers, (b) voltages and line current when cos φ ≠1 and (c) voltages and line current when cos φ = 1

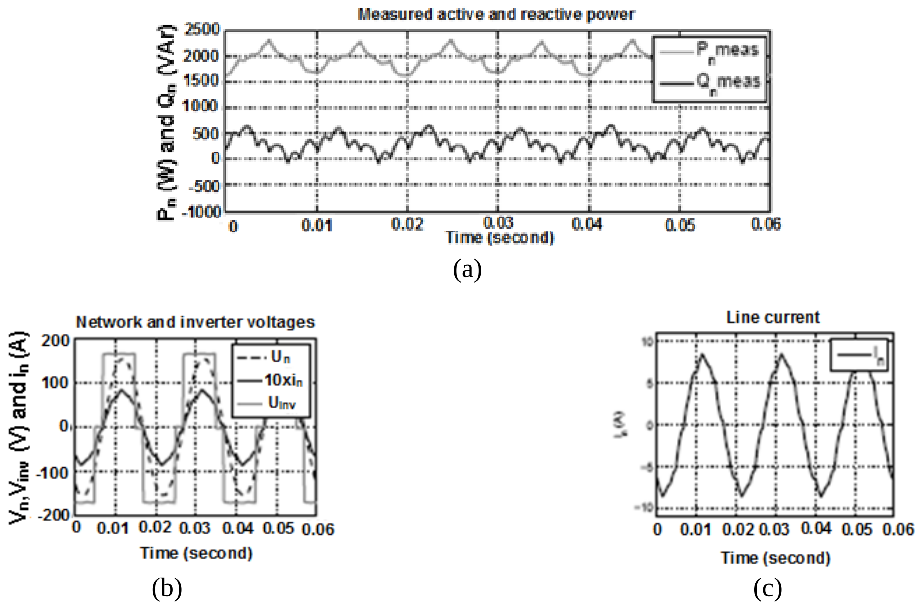


Figure 8. Experimental results: (a) measured powers, (b) voltages and line current when cos φ = 1, and (c) line current

5. CONCLUSION

A photovoltaic system is made up of numerous components. In this paper, the authors have cited and have briefly described the role of each element. Actually, power electronic inverter can be considered as the most important component, wich is used in solar power generation to correct system fluctuations that threaten grid stability. However, measurement noise in the grid voltage desynchronizes the inverter and network signals. To solve this problem, a PI-based PLL and 24-sector control of a 3P-3L-NPC inverter is proposed for grid-tied PV system synchronization. Its main advantage is a simple structure without any extra circuit. This method is mainly based on an estimation of modular period after verification of the network and the inverter angular positions A modified number of voltage sectors is proposed to control this inverter. Surprisingly, it was discovered that using 24 sectors rather than 12 or 6 sectors is feasible. This ingenious solution is used on the 3P-3L-NPC inverter, which serves as an interface between the PV system and the grid. Finally, the theoretical analysis and simulation results, which are supported by experimental measurements, demonstrate the suitability of the proposed PLL technique.

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