A Hybrid Synchronization Controller for a Grid-Connected Photovoltaic Inverter with a High Inductive Load

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Abstract. With the ongoing extension of electricity networks, traditional power systems have become increasingly incapable of meeting increased power demands. As a source that is available all year round, solar energy offers to be a promising renewable energy resource for power generation in Iraq. In this paper, a hybrid synchronization controller (HSC) based on the orthogonal method for the generation of reference control signals with PI controllers is used. The proposed HSC is designed for a single-phase photovoltaic (PV) inverter with LC filters for the supply of high-inductive load; it aims to provide (i) stable active power under variations of solar irradiance levels and (ii) low reactive power under the variation of inductive loads. The purpose of the former is to avoid overloading of the PV panels whilst the latter aims to correct the power factor at the PV inverter. A simulation was implemented in a MATLAB-Simulink-environment for the HSC, and the results demonstrated that HSC showed improved performance in terms of maximum active power transfer and power factor correction on the PV-inverter side.

Abbreviations
HSC, Hybrid Synchronization Control; PV, Photovoltaic; CSI, Current-Source Inverter; VSI, Voltage-Source Inverter; OSG, Orthogonal Signal Generator; ROSG, Reverse Orthogonal Signal Generator; PLL, phase-locked-loop.

1. Introduction
Due to increased expansion of the electrical grid, power generation has become unreliable and unstable in many cases. Renewable-energy systems have various advantages in terms of addressing this issue, including pollution reduction, wide-range utilisation possibilities, stationary installation sites, and minimised power losses. PV power units offer cost-effective operation compared with many popular types of plants [1]. However, Microgrids also offer an efficient solution for maintaining the stability of electrical grids under fluctuation in demand [2,3,4].

In [5], multiple parallel PV-inverters were implemented to increase the power quality and the efficiency of the system. Load-sharing between a PV-system and the grid was achieved by reducing the circulating currents between power converters. In [6], a simplified VAR control method for a single-phase grid-connected PV-inverter was presented. The modulation techniques were based on an asynchronous-sigma-delta with current-mode controls to reduce THD. In [7], a current control strategy for an LCL-filter for the on-grid inverter was analysed to reduce THD and improve the power factor. The method used in [7] to reduce THD in this way was active damping control.

Based on the literature as noted above, the phase-of-line-current supplied by a solar-inverter is delayed in its contribution to grid voltage due to the LC-filter and load inductance. Thus, a power-factor-correction circuit can be connected in parallel to the PV-inverter to improve the power factor of the...
grid feed and consequently to improve the power transfer from the PV array. Thus, synchronization can be varied using orthogonal method while improvement of the power factor is undertaken by adjusting reactive power (VAR) to the grid. The benefit of the proposed technique is an increase in the reliability of the PV-inverter in terms of supplying high inductive loads.

2. Description of PV-Generator with Power Converters

In general, these types of systems contain solar panels that convert solar irradiance into electrical energy. Fluctuation of voltage occurs due to changes in irradiance strength, and thus a DC voltage regulator is used to even out the voltage. A PWM-inverter is then used to convert the DC voltage into AC voltage. An LC-filter is also required to mitigate the harmonic components produced by the high frequency switching in the inverter. This system is then connected to an RL load crossing the grid, and controller is required to generate a pulse to the inverter switches. In this article, an orthogonal method with PI-controllers is proposed to generate the reference-control signal to adjust the amplitude and phase of the inverter voltage and current.

As PV is a DC source, there is no reactive-power generation. When a PV is connected to a load via a DC regulator, the voltage and current of the PV array can thus be varied by the DC regulator such that active power can be tightly controlled. A well-known technique, maximum-power-point-tracking, is used to extract maximum power from PV generators, but a DC regulator cannot inject or absorb any reactive power. When an inverter is utilised, the reactive power can be injected into the grid by varying the amplitude and phase of the power factor correction (PFC) circuit. In this research, a voltage-oriented control (VOC) method is favoured to control the PFC circuit for high inductive-loads, while reactive power can be controlled by adjusting the orthogonal component current.

Figure 1 shows a two stage PV generation system, in which the PV array is connected first to a DC regulator, then to a PWM inverter. The DC regulator extracts maximum active power from the PV array. The inverter adjusts the active power (kW) by keeping the DC voltage close to the maximum power point voltage of the PV array. In contrast, for grid connections with low inductive loads, the PWM inverter does not only track maximum active power but also adjusts reactive power to the grid by adjusting the direct component current.

Figure 1. Scheme of a grid-connected PV-inverter and PFC for active and reactive power control.
3. Topologies of Grid-Connected Inverters for PV Generators:
There are numerous different single-phase inverter topologies which should be selected based on the desired operation: the most common are (i) current-source inverters (CSI) and (ii) voltage-source inverters (VSI) [8]. Single-phase VSIs can be classified into two kinds, half-bridge and full-bridge topologies. Although, their power range is low, they are widely used in power supplies and single-phase UPS units. VSIs depend on their capacitor capability, which is determined using the following expression:

\[ v_C = C \frac{di}{dt} \]  

CSI is used to yield a stable AC-output current under variations in radiance levels. For sinusoidal-AC outputs, the magnitude, frequency, and phase should be controlled so that PV generator can be connected to the grid. To realize synchronisation conditions, it is essential to add an inductor in-series with the inverter; the value of inductance is given below:

\[ i_L = \frac{1}{L} \int v_L dt \]  

4. Design of HSC Algorithms for the PV Generator System
Along with the operation of the inverter as a stand-alone power source, extra generated power will generally be sent to the grid. In this section, the design of the HSC for grid connection with high inductive loads is demonstrated. In [9-12], as mentioned in Section 2, two types of grid-connected inverters are utilised, VSI and CSI. However, the amplitude and phase-angle of the inverter voltage and current output must be controlled in order to achieve stable output current and to permit synchronization and power factor correction. The proposed HSC is thus based on an orthogonal-method with PI-controllers. The phase angle and amplitude of the grid voltage must first be detected to achieve synchronization between the inverter and grid.

4.1 Amplitude Detection for Grid-Synchronization
In [13], an amplitude detection technique was presented whereby the amplitude and phase-angle of an inverter can be detected without a phase-locked-loop (PLL). Using this method, a fixed angular frequency (i.e. the grid angular-frequency of 314 rad/sec) is used as a reference signal. As a result, the error between the referenced angular frequency and the detected angular frequency is controlled via a PI to produce an accurate phase angle for the output current. Figures 2 to 5 show the design steps of HSC for grid synchronization and power-factor correction.

Figure 2. Amplitude detection based orthogonal method.
4.2 Control of Active and Reactive Power

The active power for the inverter is proportional to the current in phase with the grid voltage, and the reactive power output is proportional to the current in quadrature phase with the line voltage. Thus, the current reference ($i^*$), as shown in equation (3), includes two components: an active power current reference ($I_p^*$) and a reactive power current reference ($I_q^*$). From equations (3) to (6), an expression for total reference current is derived as shown in equation (7), where ($I_p^*$) and ($I_q^*$) are the peak values of the current references ($i^*$), and $\Theta$ is the estimated phase angle of the grid voltage.

Consequently, current-refereces for active-power and reactive-power can be used to adjust the inverter output current according to variations in irradiance levels, as shown in Figures (5-7) [14, 15].

\[
i^* = I_p^* + I_q^*
\]

\[
I_q^* = i^* \cos(\Theta)
\]
\[ I_p^* = i^* \sin(\Theta) \]  
\[ i^* = i^* \sin(\Theta) + i^* \cos(\Theta) \]  
\[ i^* = \sqrt{2} \left[ \frac{P^* \sin(\Theta)}{V_g} \right] + \sqrt{2} \left[ \frac{Q^* \cos(\Theta)}{V_g} \right] \]

**Figure 6.** Active-power control

**Figure 7.** Reactive-power control.

Note that the instantaneous active power and reactive power can be respectively obtained from equations (8) and (9) [15].

\[ P = \frac{(V_a I_s + V_b I_s)}{2} \]  
\[ Q = \frac{(V_a I_s - V_b I_s)}{2} \]

Finally, the reference output current is produced as shown in Fig. (7).
5. Simulation and Discussion

The PV-generator system discussed in this paper was simulated in MATLAB and Simulink. A 42.63 kW PV-array was implemented with the following specifications: voltage at maximum power point was 29 V x 10 series-connected panels per string and current at maximum power point was 7.35 A x 20 parallel strings. The DC regulator was modelled as an averaged DC Chopper (see Appendix B) and the optimal control signals (i.e. 1/(1-D)) for the ideal switch were 1.10 at 1000 W/m² and 2.57 at 400 W/m² where the irradiance level was changed at 0.2 seconds from 1000 W/m² to 400 W/m². The temperature was considered to be constant at 25 °C. The parameters of the Simulink model (see Appendix A) included the fact that the inductance of LC-filter was 1 mH and the capacitance of LC-filter was 260 µF. The resistance of the RL load was chosen to be equal to the optimal DC resistance of the PV-array at 1000 W/m², or 2 ohms, and the inductance of RL load was selected as 8 mH and 16 mH. The simulation parameters are listed in table 1.

| Parameters                        | Value    |
|----------------------------------|----------|
| Nominal power for a PV panel     | 213.15 W |
| Open circuit voltage             | 36.3 V   |
| Short circuit current            | 9.03 A   |
| Voltage at MPP (V p v)           | 29 V     |
| Current at MPP (I p v)           | 7.35 A   |
| Number of panels (for on branch) in series | 10 panels |
| Number of panels (branch) in parallel each branch includes 10 panels | 20 branches |

For medium RL load, L=8 mH; the waveforms of inverter voltage and output current are presented in Figure 8 both without (a) and with (b) the proposed HSC. It is visible that the current is in phase with inverter voltage when using the HSC. The power factor is also improved from 0.7138 (using a conventional synchronization method based on PLL [16]) to 0.9577 (with HSC), as illustrated in Figure. 9. The simulation scenario was repeated for high RL load, with L=16 mH, as shown in Figure 10, and here, the power factor also improved from 0.51 (without HSC) to 0.9778 (with HSC).
Figure 9. Inverter voltage and current when $L=8$ mH.

(a) without the proposed controller

(b) with the proposed controller
(b) with the proposed controller

**Figure 10.** Power factor and inverter power when L=8 mH, where the blue solid line is the active power (kW) and the red dashed line is the reactive power (kVAR).

(a) without the proposed controller
Figure 1. Inverter voltage and current when L=16 mH.

(a) without the proposed controller

(b) with the proposed controller
Figure 12. Power factor and inverter power when L=16 mH, where the blue solid line is the active power (kW) and the red dashed line is the reactive power (kVAR).

6. Conclusions
A hybrid synchronization control (HSC) algorithm was developed in this research project. The entire PV-generator with its power converters (for synchronization and power factor correction) was tested in MATLAB and Simulink. It was thus proven that HSC can be employed adequately under sudden changes in irradiance levels as well as under load variation. By using HSC, the power factor is enhanced from 0.7138 (normal operation) to 0.9577 at medium RL load, and from 0.51 (normal operation) to 0.9778 at high RL load. It was also shown that power factor of the PV-inverter is very close to unity. These factors lead to the final deduction that, by using the proposed HSC, the PV-generator can be safely synchronized to grid and supply high-inductive-loads. Decreasing the complexity and the cost of the power-electronic conditioners is a prospective focus for future work, as is implementing the proposed synchronized algorithm.

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Appendix A: Simulink model of the proposed HSC.

Appendix B: Simulink model of the Averaged-DC-Chopper.
