An Adaptive Hysteresis Controller for Single-Phase Grid-Connected PV Central Inverters

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ABSTRACT: An adaptive hysteresis current controller for single-phase single-stage photovoltaic central inverters is presented. The designed controller is able to eliminate harmonic distortion and to control switching frequency and to inject the current into power grid with good power quality. The simulation model of the system is developed in SIMULINK/MATLAB environment. The controller is found effective in obtaining the desired goal when the switching frequency is adequately high which leads to the synchronization of power grid voltage and inverter current and near to unity power factor.

KEYWORDS: single-phase single-stage photovoltaic central inverters, adaptive hysteresis controller, phase locked loop.

1. INTRODUCTION
Addressing the ever increasing global demand on reliable and sustainable electricity has become a main concern of electricity sector. At the moment, fossil fuel power plants are the backbone of world’s electricity generation system. Today millions are willing to enjoy the benefits of improved lifestyle and environment with much more electricity generated from the renewable energy sources [1]. Photovoltaic (PV) systems are suitable and efficient options. During the last years a lot of effort has been devoted to reduce the cost-per-watt of PV systems. The power conditioning stage is an essential part of the PV system since it must account for an optimal energy transfer from the energy source to the load. Improving the quality of the power conditioning stage is one of the key issues of future PV applications. The design of a PV power conditioning system generally consists of a two-step procedure: 1) a proper selection of the circuit topology and the elements of the power converter and 2) the design of an adequate control strategy for the chosen power conditioning stage. The latter task is important when aiming at a stable non-oscillatory dynamical behavior of the PV system [2].

For PV power inverters, the control requirements have been generally carried out by means of a strategy based on pulse-width modulation (PWM). Among the various PWM techniques, the hysteresis band current control is used very often because of its simplicity of implementation. Also, besides fast response current loop, the method does not need any knowledge of load parameters [3]. The basic implementation of hysteresis current control is based on deriving the switching signals from the comparison of the current error with a fixed tolerance band. This control is based on the comparison of the actual phase current with the tolerance band around the reference current associated with that phase [4]. However, a current control by conventional hysteresis with fixed band has many inherent disadvantages such as variable switching frequency, consequently a large amount contents harmonic distortion in the load current and so on [5]. These drawbacks motivated many authors to develop some algorithms to improve the characteristics of the hysteresis control technique. In order to ensure a constant switching frequency this paper introduces an adaptive hysteresis current controller for a single-phase single-stage grid-connected PV inverter and the phase locked loop (PLL) is added to ensure a synchronization of modulation pulses. It is shown by means of simulation in SIMULINK/MATLAB environment that the proposed controller can efficiently fulfill the desired objectives.

2. GRID-CONNECTED PV (GPV) SYSTEM
Fig.1. shows the GPV system considered in this paper. The system consists of an array of PV panels connected to the utility grid by means of full-bridge inverter. Transferring the PV panels’ energy to the utility grid is the role of GPV systems, so the main requirement of the system is to deliver a sinusoidal current in phase with the utility grid. In this paper, it is assumed that all PV panels are linked to a unique power inverter unit, known as “central inverter” [6].
2.1. Modelling PV generator

The typical behavior of a crystalline silicon PV cell is modeled as follows:

\[
i_{pv\,cell} = I_{g\,cell}(G) - I_{sat\,cell}(T) \left[ \exp \left( \frac{v_{pv\,cell}(T)}{\eta_{T\,cell}(T)} \right) - 1 \right]
\]

where \( i_{pv\,cell} \) and \( v_{pv\,cell} \) are the cell current and voltage, respectively; \( I_{g\,cell}(G) \) is the generated current due to the incident solar irradiance \( G \); \( \eta \) is the PV cell emission coefficient, \( I_{sat\,cell}(T) \) is the reverse saturation current of PV cell p-n junction that varies with temperature \( T \), \( v_{T\,cell}(T) \) is the p-n junction thermal voltage which also changes with temperature. Since the variations of temperature and irradiance are slow compared to the dynamics of practical power inverters, it can be assumed that they do not change.

The electrical behavior of PV array is defined as follows [6]:

\[
i_{pv} = \Lambda - \rho(v_{pv})
\]

(2)

where \( v_{pv} \) and \( i_{pv} \) are the PV array voltage and current, respectively, and \( \Lambda \) represents the part of the photovoltaic generator current that depends on the solar irradiance. The last term of (2) denotes the direct link between the voltage of photovoltaic generator and the associated current, i.e.

\[
\rho(v_{pv}) = \psi \exp(\alpha v_{pv})
\]

(3)

Where \( \psi \) and \( \alpha \) represent positive parameters of the photovoltaic generator. Referring to the equation of the PV cell (1), the parameters of this model can be defined as \( \Lambda = (I_{g\,cell} + I_{sat\,cell})n_p \), \( \psi = I_{sat\,cell} n_p \) and \( \alpha = (n_s)/(\eta_{T\,cell}) \) where \( n_s \) and \( n_p \) are the number of PV cells connected in series and parallel, respectively.

2.2. Power conditioning system

In Fig. 1, \( x_1 \) and \( x_2 \) are the average values of input capacitor voltage and the output inductor current, respectively. \( v_g \) is a sinusoidal with a constant amplitude \( A \) and constant frequency \( \omega \); the switch control signals for triggering the inverter are generated via control scheme.

3. Controller Design

In order to maximum PV energy amount transferring to the utility grid by the inverter of Fig. 1, the following is required:

- to deliver a sinusoidal current in phase with the utility grid;
- to regulate the input capacitor voltage to a value that assures maximum power extraction from the PV array.

3.1. Hysteresis current controller (HCC)

The hysteresis band control method is a simple and common form of closed-loop control. The output of the hysteresis controller is the converter switching states, so in HCC there is no PWM modulator block, which simplifies the structure and improves the dynamics. Hysteresis band control is widely used because of its ability to be simply implemented. Besides the fast response, the inherent peak current limiting capability and excellent dynamic performance that it offers, it does not require an accurate knowledge of the load parameters [7]. The hysteresis controller can be made with either a current or a voltage loop.

A secondary section heading is enumerated by a capital letter followed by a period and is flush left above the section. The first letter of each important word is capitalized and the heading is italicized.

Fig. 2 shows current mode implementation of the basic hysteresis controller. The basic operation of the current mode hysteresis controller is: The output inductor integrates the differential voltage between the output voltage of the power stage and the output voltage of the amplifier. If the output voltage of the amplifier can be considered constant within one switching period, the integration results in a saw-tooth shaped inductor current, which is subtracted from the reference current programming voltage, and fed into a hysteresis window to control the switching frequency by controlling the time-delay trough the controller loop [4].

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The biggest drawback with basic hysteresis controllers used in a lot of applications is the non-constant switching frequency. In the ideal model for a hysteresis controller, the switching frequency is dependent on the modulation index, M, by:

\[
f_s(M) = f_s(0.1 - M^2)
\]

The variation in switching frequency basically causes two main functional problems: Increasing high frequency ripple voltage on the output at high modulation index caused by less attenuation of the lower switching frequency’s harmonics, and reducing open loop bandwidth and -loop gain, causing increased distortion as well.

3.2. Proposed adaptive hysteresis current controller (AHCC)
An adaptive hysteresis current controller, shown in Fig. 3, is introduced in order to ensure a constant switching frequency and the phase locked loop (PLL) is added to ensure a synchronization of modulation pulses. An acceptable performance is achieved when the hysteresis bandwidth is quite narrow. This narrow bandwidth translates to a high average converter switching frequency \(f_s\) and increased switching losses.

4. SIMULATIONS
The proposed control scheme is developed in SIMULINK/MATLAB environment, Fig. 4, where it is assumed that \(L = 2mH\), \(C = 2.2mF\) and \(v_g = 312 \sin(100\pi)\).

Parameters of PV array are mentioned in Table.1 in details.
For the proposed controller, PLL Parameters are \(f_Z = 500Hz\) \(k_p = 0.5\) and Desired Switching Frequency is \(f_d = 5KHz\).
Results are illustrated in Figs. 5, 6 and 7. In Fig. 5, the scaled grid voltage, \(v_{g12}\), is shown.

As it is observed in Figs. 6 and 7, the system is able to keep the commanded voltage value for maximum power extraction from the PV array while maintaining at all times a sinusoidal current in phase with the grid voltage.

5. CONCLUSION
An adaptive hysteresis current controller is proposed for single-phase single-stage grid-connected PV central inverters. The approach will derive a global
asymptotically stable closed-loop system. Having a sinusoidal current in phase with the voltage grid is also well fulfilled and the capacitor voltage can assure maximum power extraction from the PV array while the harmonic distortion is eliminated and switching frequency is controlled.

REFERENCES