Current-Control Inverter Schemes for a Grid-Connected PV Generator

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Abstract—Photovoltaic Generators (PVGs) are one of the popular renewable energy sources (RESs), which achieve 47% of RES in microgrids. The main components of the proposed system are: (i) a PVG considering extremum operating conditions, the irradiance change is 400-1000 W/m² and the temperature change is 25-60 °C; (ii) a DC-DC boost converter used for regulating the variable DC-link voltage via an inner voltage-loop controller (iii) a single-phase H-bridge inverter controlled by an outer current-loop controller for implementing the maximum power point tracking (MPPT) algorithm at grid side; (iv) an inductive power filter for improving the total harmonic distortion (THD) of the grid current. In this paper, the grid current is controlled to follow the maximum power point (MPP) current considering the losses when transferring the DC power to the grid. Two current-loop controllers are implemented, which are: (i) hysteresis current controller (HCC) and PI current controller (PICC). The proposed design is validated in MATLAB/SIMULINK and the simulation results show significant improvement in power quality, Total Harmonic Distortion (THD) of the output grid current is less than 2% and the power factor is close to unity.

1. Introduction
The expected total global energy generation from renewable, sources by the end of 2018 is 2,017 GW [1]. One major renewable energy source is photovoltaic (PV), which comprises about 47% of recently installed renewable power generation [2][1]. The major drawback to renewable energy sources, including PV and wind power, is that they fluctuate and can be only intermittently, reliable for energy generation because they rely on natural, not controllable factors such as the sun and wind. Therefore, an interface system between renewable energy source and power grid should be provided to meet the requirements of the power grid. In this paper a single-phase Voltage Source Inverter (VSI) is proposed as interface between a PV boost converter and power grid. Designing reliable and highly efficient power converters is the most important part in the renewable power generation. Chan and Pui W., 2010 in [3], introduced design of a DC-DC boost converter, using a microcontroller in the control system to track and provide pulse-width-modulation signal to control the output voltage of the boost converter. Putri, et al., 2016 in [4], presented a hysteresis current controller to reduce the losses of a three-phase grid-connected inverter. Zakzouk, et al., 2016 [5], proposed a sensorless technique for DC-link voltage control of a grid connected single phase two stage PV converter. Ali J. M., et al., 2018 [6], proposed a DC-link voltage control technique based on particle Swarm optimization method for grid connected two stage PV inverters. This paper proposed a system with boost converter used for
controlling the variable DC-link voltage via an inner voltage-loop controller and a single-phase H-bridge inverter with an outer current-loop controller for implementing the maximum power point tracking (MPPT) algorithm at grid side. The proposed system is implemented in MATLAB R2017b/SIMULINK and the simulation results show the robustness of the proposed controllers under the EOCs. The organization of this paper is as follows; Section 2, describes the Voltage Source Inverter VSI. Section 3, explains the type of current controller. Section 4, explains the design of DC-link and voltage controller. Section 5, explains Power filter design. Section 6 describes grid current controller based on MPPT. Section 7, describes the design calculations of the proposed system section 8 explains the simulation results and discussion.

2. Voltage Source Inverter VSI

VSIs are step-down converters, where the input DC voltage is greater than AC output voltage [7]. In VSI, a large capacitor connected in parallel with the input DC side [8]. A tie-line inductor is used along with the VSI to boundary the current flow to the utility grid. Another feature of VSIs is that, they can be operated in both voltage control (VCM) mode, and current control mode (CCM) [9]. The self-commutated VSI structure is shown in Figure 1. In this work H-bridge inverter topology is chosen due to its simplicity and high efficiency [10].

![Figure 1: Voltage source inverter VSI](image)

3. Current control schemes for grid-connected inverters

Various controllers have been developed for inverters, some of these are: Proportional-integral (PI) controllers [11]. Deadbeat control (DBC) [12], Proportional Resonant control (PRC) [7], Predictive control (PD) [13], Repetitive control (RB) [14], Direct power control (DPC) [15], Robust controllers (RB) [16], Hysteresis current control (HCC) [17], Sliding mode controllers (SMC) [18]. However, these control schemes have been discussed and analyzed as advantages and drawbacks in [9][19][20]. In this paper, two methods for current control are designed and implemented; which are PI control and the HCC.

3.1 PI Controller

Proportional-integral (PI) controller is well known technique. The benefits of PI controllers are; feasibility and ease of implementation, well defined harmonic spectrum, absence of DC-side ripple output voltage, fixed switching frequency. In tuning the PI controller, the parameters must be prudently tuned with a trade-off between maintaining the system stability and achieving an acceptable dynamic response during transient [4].

3.2 Hysteresis Current Control (HCC).

Hysteresis current controllers are categorized as direct current control (DCC) [4] but non-linear type [9]. The hysteresis band current control is adopted very often due to its significant advantages which
are simplicity of implementation direct overcurrent protection, and robustness to impedance variations [17]. Also has good accuracy, and unconditioned stability. This control method has undesirable features such as uneven switching frequency that causes noise and difficult designs for input filters [21]. It does not have any limit for maximum switching frequency hence, additional circuit can be used for limiting the frequency [22]. The block diagram of HCC is shown in Figure 2. The hysteresis band width h is calculated by [19]:

\[ h = \frac{(V_{dc}^2 - V_g^2)}{4V_{dc}L_{ac}f_s} \]  

(1)

where \( V_{dc} \) is the DC-link voltage, \( V_g \) is the grid voltage, \( L_{ac} \) is the filter inductance at AC-side and \( f_s \) is the switching frequency of the inverter.

4. DC-Link design

4.1 Size selection of DC-link capacitor

The minimum capacitance of the DC-link capacitor can be obtained given the magnitude of the maximum allowed ripple voltage \( V_{r_{max}} \) as [23]:

\[ C_{dc} = \frac{S_{rated}}{4\pi f_a V_{dc} V_{r_{max}}} \]  

(2)

where \( C_{dc} \) is the DC-link capacitor, \( S_{rated} \) is the inverter output rated power, \( f_a \) is the utility frequency 50 Hz, \( V_{dc} \) is the DC-source voltage, and \( V_{r_{max}} \) is the voltage ripple, normally kept about 10% of total voltage [6].

4.2 DC-Link voltage level

The grid voltage should be less than DC-link voltage level to guarantee power flow and enforced current injection to the utility grid. As shown by equation (3) [24].

\[ V_{dc} = \frac{\sqrt{2}V_g}{m_a} \]  

(3)

where \( V_g \) is RMS grid voltage (e.g. 230 V) and \( m_a \) is the modulation index (0 \( m_a \leq 1 \)).

Figure 2: Hysteresis current controller.
5. Power filter design

5.1 Filter as Grid Interface
According to the international standards IEC61727, IEEE1547, [25]. In power system, three categories of passive filters can be used to improve THD, these are the L, LC and LCL filters. More related information can be found in [26].

5.2 L Filter type
The L filter type is suitable for converters with high switching frequency [27]. It has excellent performance in terms of voltage to current conversion. L filter design is easy implementation but in application more than several kilowatts it becomes costly because of using a huge filter reactor. Furthermore, the system dynamic response becomes poor. The smoothing inductor $L_{ac}$ for single-phase inverters such that inverter modulation index amplitude, $(m_a) \leq 1$. The inductance of the L filter can be calculated from Equation (4) [28].

$$L_{ac} = \frac{V_{dc}}{2f_{sw} \Delta I_g} \frac{1}{2} \sqrt{\frac{1}{2} m_a^2 - \frac{8}{3\pi} m_a^3 + \frac{3}{8} m_a^4}$$  \hspace{1cm} (4)$$

where $L_{ac}$ is the filter inductance at AC-side, $V_{dc}$ is the DC-source voltage, $f_{sw}$ is the switching frequency of the inverter, $\Delta I_g$ is the effective value of utility current ripples, and $m_a$ is the modulation index $(m_a \leq 1)$. In order to design the suitable output filter at AC side, the $THD_l$ should verify the following expression [28].

$$THD_l = \frac{\Delta I_g}{I_{g(1)}} \times 100 \leq THD_l(required)$$  \hspace{1cm} (5)$$

where: $\Delta I_g$ is the effective value of utility current ripples, $I_{g(1)}$ is the effective fundamental component of utility current which can be calculated according to (6), neglected converter losses.

$$I_{g(1)} = \frac{P_g}{V_{i, output}}$$  \hspace{1cm} (6)$$

6. Grid current controller based on MPPT
In this paper, two control methods PI and HCC are used. The amplitude of the reference grid current is estimated depending on the tracked maximum PV power value.

For lossless power converters, $I_{gref}$ is estimated in the following expressions:

$$P_{pv} = \frac{1}{2} \int_0^{2\pi} p_g \, dw = P_g$$  \hspace{1cm} (7)$$

$$I_{gref} = \frac{P_{pv}}{V_g}$$  \hspace{1cm} (8)$$

RMS current is then multiplied by $\sqrt{2}$ to find the peak AC current as follows:

$$I^*_{gref} = \sqrt{2} \times I_{gref}$$  \hspace{1cm} (9)$$

Since, the grid voltage amplitude is:

$$V^*_g = \sqrt{2} \times V_g$$  \hspace{1cm} (10)$$

By considering the losses of the power-electronics converters, the reference grid-current amplitude must be re-estimated by evaluating the efficiency for the overall system. The efficiency for the entire system is given in Equation (11):
\[ \eta_{all} = \eta_{mppt} \times \eta_{boost} \times \eta_{inv}. \] (11)

where \( \eta_{mppt} \) is the MPPT algorithm efficiency, \( \eta_{boost} \) is the boost converter efficiency and \( \eta_{inv} \) is the inverter efficiency.

The injected power into the grid and the RMS current, \( I_{gref} \), (considering losses) is given as follows:

\[ P_g = \eta_{all} \times P_{pv} \] (12)

\[ I_{gref} = \frac{\eta_{all} \times P_{pv}}{V_g} \] (13)

Hence, the magnitude of the grid current, \( I_{gref}^* \), is as follows:

\[ I_{gref}^* = \sqrt{2} \times \eta_{all} \times I_{gref} \] (14)

7. Design calculations of the proposed system

In this paper, the best and the worst power generation are considered to design the power converters, where 1000 W/m² and 25 °C is considered as the best case and 400 W/m² and 60 °C is considered as the worst case [29]. According to these operating conditions, the range of input DC voltage are between 212 V and 177 V. Thus, \( V_{ref} \) can be calculated using equation (3).

\[ V_{dc} = V_{ref} = \frac{\sqrt[2]{V_{inv}}}{mA} = \frac{\sqrt[2]{230}}{0.8} = 230 = 406.5 \text{ V} \]

The DC-link capacitor value can be calculated using equation (2):

\[ C_{dc} = \frac{S_{rated}}{4\pi f_0 V_{dc} V_{r_{max}} } = 624.5 \mu \text{F} \]

The theoretical calculations according to equations (3-10) are given in Table 1.

| Irradiance and Temperature Levels | \( V_{dc} \) (V) | \( V_g \) (V) | \( V_{g_{max}} \) (V) | \( I_{gref,}\) (A) | \( I_{gref}^* \) (A) | \( I_{gref(t)} \) (A) | \( P_g \) (W) |
|----------------------------------|----------------|-------------|-------------------|----------------|----------------|----------------|------------|
| 1000 W/m² at 25°C               | 406.5         | 230         | 325.269           | 7.047          | 9.967          | 9.967 sin(314.15t) | 1621       |
| 400 W/m² at 60°C                |               |             |                   | 2.38           | 3.365          | 3.365 sin(314.15t) | 547.4      |

For losses consideration:
\( \eta_{mppt} = (98 - 99)\% \), \( \eta_{boost} = 96\% \), \( \eta_{inv} = (98-95)\% \) choosing 0.96 Hence, the efficiency for the overall system according to Equation (11):
\[ \eta_{all} = 0.98 \times 0.96 \times 0.96 = 90\% \]

The theoretical calculations according to Equations (12-14) are listed in Table 2.

**Table 2:** Theoretical calculations with losses consideration.

| Irradiance and Temperature Levels | \( V_{dc} \) (V) | \( V_g \) (V) | \( V_g' \) (V) | \( I_{gref} \) (A) | \( I_{gref}(t) \) (A) | \( P_g \) (W) |
|----------------------------------|-----------------|----------------|----------------|-----------------|-----------------|--------------|
| 1000 W/m² at 25°C                | 406.5           | 230            | 325.269        | 6.343           | 8.97 sin(314.15t) | 1458.9       |
| 400 W/m² at 60°C                 |                 | 2.142          | 3.029          | 3.029 sin(314.15t) | 492.66         |

By choosing an L- filter, \( I_{g(1)} = I_{gref} \), and \( THD_L = 2\% \), the design calculations are summarized in Table 3 using Equations (4) and (5).

**Table 3:** The design results for suitable L-filter value at different environmental conditions.

| Irradiance and Temperature Levels | THD | \( L_{ac} \) (mH) | \( I_{g(1)} \) (A) | \( \Delta I_g \) (A) | \( L_{ac} \) (mH) Considering Losses | \( I_{g(1)} \) (A) Considering Losses | \( \Delta I_g \) (A) Considering Losses |
|----------------------------------|-----|------------------|-------------------|-----------------|-------------------------------------|--------------------------------------|--------------------------------------|
| 1000 W/m² at 25 ºC               | 5%  | 2                | 0.352             | 2.4             | 6.343                               | 0.317                                |                                      |
|                                  | 4%  | 2.7              | 0.282             | 3.0             |                                     |                                      |                                      |
|                                  | 3%  | 3.6              | 0.211             | 4.0             |                                     |                                      |                                      |
|                                  | 2.5%| 4.4              | 0.176             | 4.8             |                                     |                                      |                                      |
|                                  | 2%  | 5.5              | 0.140             | 6.0             |                                     |                                      |                                      |
|                                  | 1%  | 11               | 0.070             | 12              |                                     |                                      |                                      |
| 400 W/m² at 60 ºC                | 5%  | 6.5              | 0.199             | 7.2             | 2.142                               | 0.1071                               |                                      |
|                                  | 4%  | 8.0              | 0.952             | 9.0             |                                     | 0.0856                               |                                      |
|                                  | 3%  | 11               | 0.071             | 12              |                                     |                                      |                                      |
|                                  | 2.5%| 13               | 0.059             | 14              |                                     | 0.0535                               |                                      |
|                                  | 2%  | 16               | 0.047             | 18              |                                     | 0.0428                               |                                      |
|                                  | 1%  | 32               | 0.024             | 36              |                                     | 0.0214                               |                                      |

8. Validation of the proposed system via simulation

8.1 Simulation results of boost converter with a voltage PI controller

The system performance is investigated in two cases. In case 1 for time steps 0 to 0.5 seconds the steady state performance is evaluated by directly feeding to the boost converter ideal input voltage (212.4 V) which represents input parameters of 1000 W/m² irradiance and 25 ºC temperature for PVG. In case 2 for time steps 0.5 to 1 seconds the steady state performance is evaluated by directly feeding input voltage (177 V) which represent input parameters of 400 W/m² irradiance and 60 ºC temperature for PVG.

8.1.1 Simulation results of boost converter with PI controller at 1000W/m², 25ºC
For the time-steps from 0 to 0.5 seconds the values of duty cycle, output voltage, and current are investigated at steady state. For this simulation of boost converter with PI controller, the boost converter is assumed to have the following parameters $V_{in}=212.4 \text{ V}$, $V_c=406.5 \text{ V}$, $C_d=750 \mu\text{F}$. And the PI controller is assumed to have the following parameters, $K_p=0.5$ and $K_i=50$. Figure 3-a shows that the duty cycle value resides around 0.479 with very small fluctuations between the highest and the lowest peak. Figure 3-b shows the steady state response and output voltage showing that the PI controller has enhanced the output voltage. For a given reference voltage, its value resides around 406.5 V with DC-link voltage ripples of ±0.14%.

Figure 3-a: The duty cycle value  
Figure 3-b: The reference and output voltage value

8.1.2 Simulation results of boost converter with PI controller at 400W/m², 60°C

The simulation results present the steady state performance of the boost converter with PI controller tested under worst weather conditions; 400 W/m² irradiance and 60 °C temperature. For the time-steps from 0.5 to 1 seconds the values of duty cycle, output voltage, and current are investigated at steady state. For this simulation of converter and PI controller, the boost converter is assumed to have the following parameters $V_{in}=177 \text{ V}$, $V_c=406.5 \text{ V}$, $C_d=750 \mu\text{F}$. And the PI controller is assumed to have the following parameters, $K_p=0.5$ and $K_i=50$. Figure 4-a, shows the duty cycle value resides around 0.564 with very small fluctuations. In Figure 4-b, the steady state response shows that the PI controller has enhanced and regulates the output voltage. For a given reference voltage, its value resides around 406.5 V with DC-link voltage ripples of ±0.05%.

Figure 4-a: The duty cycle value  
Figure 4-b: The reference and output voltage value

8.2 Simulation Results and Discussion of proposed grid connected inverter with current controller

The results obtained using two controllers:

1. The Proportional-Integral (PI) controller: The system is tuned by choosing a small value for $K_p$ and zero for $K_i$. Then, the value of $K_p$ gradually increased until obtaining a sustained oscillation in the $V_{dc}$. Among many controller gains, the suitable controller gains are $K_p=10$ and $K_i=50$. The transfer function of the PI controller is described by:

$$G_c(s) = K_p + \frac{K_i}{S} = 10 + \frac{50}{S}$$

2. The Hysteresis Current Control HCC controller: To investigate the system performance two cases are considered. In the first case for the time steps from 0 to 0.5 seconds, the steady state performance is evaluated by directly feeding ideal input voltage $V_{dc}=406.5 \text{ V}$ to the VSI
according to formula 3, and ideal input reference current amplitude with losses consideration 8.97 A according to formula (15), into the current controller loop. These represent input parameters of 1000 W/m² irradiance and 25 °C temperature for PVG. In the second case for the time steps from 0.5 to 1 seconds, the steady state performance is evaluated by directly feeding the same voltage to the VSI, and ideal input reference current amplitude 3.029 A with losses consideration into the outer current controller loop. These represent input parameters of 400 W/m² irradiance and 60 °C temperature for PVG, as shown in Figures 5-a. The simulation results of amplitude and instantaneous reference current is represented in Figures 5 a, b, and c.

![Simulation results amplitude and instantaneous reference current.
](image)

8.2.1 Simulation Results and Discussion of proposed inverter–grid contacted with current controller at 1000W/m², 25°C

The time-steps considered in this case from 0 to 0.5 seconds, the results investigated the $V_{dc} = 406.5$ V, and ideal $I_{gref}$, with losses consideration 8.97 A. Figures 6-a and 6-b and Figures 6-c and 6-d show the output current waveforms and FFT analysis at STC. using HCC and PIC respectively

![Output current and FFT analysis at (1000W/m², 25°C using HCC)](image)

![Output current and FFT analysis at (1000W/m², 25°C using PIC)](image)

8.2.2 Simulation Results and Discussion of proposed inverter–grid contacted with current controller at 400W/m², 60°C.

The time-steps considered in this case from 0.5 to 1 seconds, the results investigated the $V_{dc} = 406.5$ V, and $I_{gref}$, with losses consideration 3.029 A. Figures 7-a and 7-b and Figure 7-c and 7-d show the output current waveform and FFT analysis at 400W/m², 60°C using HCC. PIC. respectively
Figure 7: (a) Output current and (b) FFT analysis at (400W/m², 60°C using HCC).

Figure 7: (c) Output current and (d) FFT analysis at (400W/m², 60°C using PIC).

Simulation results, shown in Figures 5, 6, and 7 are summarized in Table 4.

Table 4. System performance for the proposed system with the outer current controller.

| Controller Type | Irradiance and Temperature Levels | $V^g$ (V) | $V_{g(1)}^g$ (V) | $I_{ref}^g$ (A) | $I_g^g$ (A) | $I_{g(1)}^g$ (A) | THD$_v$ | THD$_l$ | Testing Time (s) |
|-----------------|----------------------------------|-----------|----------------|----------------|-------------|----------------|--------|--------|-----------------|
| PI              | 1000W/m², 25 °C                  | 326.6     | 325.5          | 8.97           | 8.977       | 8.896         | 1.21%  | 0.53%  | 0.5             |
| HCC             |                                  | 326.6     | 325.5          | 2.02%          | 0.49%       | 0.5            |        |
| PI              | 400W/m², 60 °C                   | 326.4     | 325.3          | 3.029          | 3.041       | 2.987         | 2.02%  | 1.47%  | 0.5             |
| HCC             |                                  | 326.4     | 325.3          | 2.02%          | 1.61%       | 0.5            |        |

From Table 4, it is noted that in case of HCC, the allowable actual injected current is 8.918 A, which is close to the reference value (e.g. 8.97 A). The reference current is produced from the MPPT controller considering the efficiency of all converters. It is seen that the THD in the case of using the HCC is enhanced compared with the case of using the PI controller. It is demonstrated that THD for all cases is less than 5%. These issues verify the robustness of the proposed controllers.

8.3 Simulation results and discussion for validation of interfacing subsystems using the complete system

Figures 8-12 show the validation results in Table 4. The ripple becomes a little more than at previous testing because of causes and effects of fluctuation in DC-link, power decoupling and power balance principle). Figure 12 shows the power factor, which is close to unity.
Figure 8: (a) Output current and, (b) FFT analysis at (1000W/m², 25°C using HCC).

Figure 9: (a) Output current and, (b) FFT analysis at (400W/m², 60°C using HCC).

Figure 10: (a) Output current and (b) FFT analysis at (1000W/m², 25°C using PIC).

Figure 11: (a) Output current and (b) FFT analysis at (400W/m², 60°C using PIC).
Conclusion
A robust voltage controller for the boost converter is designed considering the variations in the irradiance and temperature to verify stable power flow from the PVG to the DC-Link of the inverter. The calculated and the simulation results are in good agreements, the error between the output actual AC and the reference AC MPP current is very close due to the effectiveness of the proposed current controller, which are HCC and PICC. It is clear, for normal operation (at STC) and worst operation (at 400W/m², 60°C) conditions that THD of the output AC current is always less than 2% and the power factor is close unity.

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**Appendix A:** The equivalent Simulink model of the proposed system.