2013

Power control of single-stage PV inverter for distribution system volt-var optimization

Xiao Liu
University of Kentucky, xiao.liu@uky.edu

Click here to let us know how access to this document benefits you.

Recommended Citation
Liu, Xiao, "Power control of single-stage PV inverter for distribution system volt-var optimization" (2013). Theses and Dissertations--Electrical and Computer Engineering. 36.
https://uknowledge.uky.edu/ece_etds/36

This Master's Thesis is brought to you for free and open access by the Electrical and Computer Engineering at UKnowledge. It has been accepted for inclusion in Theses and Dissertations--Electrical and Computer Engineering by an authorized administrator of UKnowledge. For more information, please contact UKnowledge@lsv.uky.edu.
STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained and attached hereto needed written permission statements(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine).

I hereby grant to The University of Kentucky and its agents the non-exclusive license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless a preapproved embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student’s advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student’s dissertation including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Xiao Liu, Student

Dr. Aaron M. Cramer, Major Professor

Dr. Caicheng Lu, Director of Graduate Studies
Power control of single-stage PV inverter for distribution system
volt-var optimization

THESIS

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Electrical Engineering in the College of Engineering at the University of Kentucky

By

Xiao Liu

Lexington, Kentucky

Director: Dr. Aaron M. Cramer, Assistant Professor of

Lexington, Kentucky

2013

copyright © Xiao Liu 2013
ABSTRACT OF THESIS

POWER CONTROL OF SINGLE-STAGE PV INVERTER FOR DISTRIBUTION SYSTEM VOLT-VAR OPTIMIZATION

The output power variability of intermittent renewable sources can cause significant fluctuations in distribution system voltages. A local linear controller that exploits the capability of a photovoltaic inverter to provide both real and reactive power is described. This controller substitutes reactive power for real power when fluctuations in the output of the photovoltaic source are experienced. In this way, the inverter can help mitigate distribution system voltage fluctuations. In order to provide real and reactive to the grid, a three-phase grid-connected single-stage photovoltaic system with maximum power point tracking and power control is described. A method of reducing the current harmonic caused by resonance of the LC filter and transformer is presented. The local linear controller is examined using an example distribution system, and it is found that the controller is effective at mitigating voltage violations. The photovoltaic control system is examined using three-phase single-stage PV inverter system. The power control and damping system show good performance and stability under rapid change of irradiance.

KEYWORDS: Distributed power generation, photovoltaic systems, power control, voltage control, virtual resistance damping.

Xiao Liu

December 11th, 2013
POWER CONTROL OF SINGLE-STAGE PV INVERTER FOR DISTRIBUTION SYSTEM
VOLT-VAR OPTIMIZATION

By

Xiao Liu

Aaron M. Cramer
Director of Thesis

Caicheng Lu
Director of Graduate Studies

December 11th, 2013
Date
ACKNOWLEDGEMENTS

I would like to thank my parents and wife for their support and love.

I would like to thank my advisor, Dr. Aaron M. Cramer for his encouragement, patience and support to my thesis work. He always gives me confidence.

I would like to thank my committee members, Dr Yuan Liao and Dr. Yuming Zhang for their professional support.

I would like to thank my friends, Fei Pan and Hanling Chen for their help.
# Contents

List of Tables ................................................. v
List of Figures ................................................ vi

1 Introduction ................................................. 1
  1.1 Introduction ........................................... 1
  1.2 Thesis Outline ........................................ 3

2 Background .................................................. 5
  2.1 Photovoltaic Array Characteristics ...................... 5
  2.2 Hysteresis Current Controller ............................ 8

3 Control of The Proposed System ............................. 10
  3.1 Reactive Power Control .................................. 10
    3.1.1 Sensitivity Minimization vs. Violation Optimization .. 13
    3.1.2 Per Phase vs. Average Phase .......................... 14
    3.1.3 Local Bus Voltage vs. Global Bus Voltages ............ 14
    3.1.4 Summary .............................................. 15
  3.2 Control of the PV Inverter System ...................... 16
    3.2.1 Ripple Correlation Control .......................... 16
    3.2.2 Power Control ........................................ 17
    3.2.3 Phase Lock Loop ..................................... 19
    3.2.4 Virtual Resistance Damping System .................. 21

4 Simulation Results .......................................... 25
  4.1 Simulation Results of Local Linear Reactive Power Control .. 25
  4.2 Simulation Results of PV Inverter Systems ............... 33
    4.2.1 Simulation Results With Constant Power Supply ....... 33
    4.2.2 Simulation results of whole PV inverter system ....... 37

5 Experiments .................................................. 41
  5.1 Experimental Results .................................... 41

6 Conclusion and Future Work ................................ 49
  6.1 Conclusion .............................................. 49
  6.2 Future Work ............................................ 50

Bibliography .................................................. 51

Vita .............................................................. 54
List of Tables

4.1 Sensitivity Factors ........................................... 26
4.2 Substitution Rates ......................................... 27
4.3 System Voltage Performance Metrics .................. 28
4.4 Simulation Parameters .................................... 33
4.5 PV and RCC Parameters .................................. 38
## List of Figures

2.1 Basic equivalent circuit of PV cell ........................................... 5  
2.2 P-V curve ................................................................. 7  
2.3 I-V curve ................................................................. 7  
2.4 MPP under different irradiance ............................................. 8  
2.5 One branch of three phase inverter ...................................... 9  
2.6 Hysteresis current control .................................................. 9  
3.1 Proposed control system ................................................... 11  
3.2 Diagram of RCC .......................................................... 17  
3.3 Diagram of PLL method .................................................... 20  
3.4 Equivalent circuit for the LC filter and transformer ................. 21  
3.5 Equivalent circuit for LC filter and transformer and damping system .................................................. 22  
3.6 Diagram of virtual resistance damping method ....................... 23  
3.7 Bode plot of transfer functions with and without damping system .................................................. 24  
4.1 Five-bus distribution system ............................................. 27  
4.2 PV output power .......................................................... 29  
4.3 Voltage magnitude at local bus .......................................... 31  
4.4 Voltage magnitude at bus 3 ............................................. 32  
4.5 Simulation results of currents and voltage without damping system .................................................. 34  
4.6 Simulation results of currents and voltage with damping system .................................................. 35  
4.7 Simulation results of power with and without damping system .................................................. 37  
4.8 Simulation results of PQ injection ...................................... 39  
4.9 Simulation results of currents and voltage .................................................. 40  
5.1 LC filter ................................................................. 42  
5.2 PCB board ................................................................. 42  
5.3 Three-phase inverter ...................................................... 43  
5.4 Experimental results of hysteresis current control .................. 44  
5.5 Experimental results of PLL ............................................. 46  
5.6 Experimental results of injection current 1 .......................... 47  
5.7 Experimental results of injection current 2 .......................... 48
Chapter 1

Introduction

1.1 Introduction

Solar energy is a clean and renewable energy source. It is an important way to relieve the energy crisis in the future. The development of solar energy has grown rapidly in recent years. From 2006 to 2011, the increasing rate of annual installations of photovoltaic (PV) systems is 53% per year in the United States [1]. The average price to install PV systems continues to fall. It can be expected that more and more PV generation will be added into the electric utility grid.

The integration of renewable resources into electric power systems is an important goal, but it involves significant technical challenges. A particular challenge associated with intermittent renewable sources such as PV generation is managing the effect of variations in output power on distribution system voltages. PV sources will cause local increases in system voltages when supplying real power. These PV sources generally employ maximum power point tracking (MPPT) in order to make the most effective use of the incident solar irradiance. Therefore, as the irradiance varies (e.g., due to passing clouds), the PV source must vary its output power. Such cloud transients have been observed to cause irradiance to change by as much as 60% per second [2,3]. Such
variations have significant impacts on the voltages in the distribution system and will have even greater impacts as the level of renewable penetration in distribution systems continues to increase. Furthermore, these variations occur too rapidly for traditional distribution system regulation equipment, such as tap changing transformers and switched capacitor banks to respond to them appropriately.

In this thesis, a local linear controller is studied in which the PV inverter responds to variations in its real power output by varying its reactive power output [4]. In this way, the inverter substitutes reactive power production for real power production in order to improve system voltages. It has been widely noted that the reactive power capability of inverter-based distributed generation can be used to improve distribution system operation (e.g., [5, 6]). For example, previous work has discussed the integration of MPPT with real and reactive power control of the PV inverter [7, 8]. In other work, reactive power is dispatched as part of the distribution system volt/var control strategy [9–15]. Herein, the reactive power capability of the inverter is employed to mitigate system voltage variations caused by short-term variability of the PV source. Furthermore, unlike in other studies [4, 16–20], the local linear controller does not require high-bandwidth communication with the distribution system controller in order to improve voltage quality.

To output the dispatched reactive power in PV system, a power control system for the three-phase grid-connected single-stage PV inverter has been studied. To increase the efficiency of the PV system, an MPPT must be implemented in the PV control system. In this thesis, the MPPT algorithm is based on ripple correlation control (RCC) [21]. RCC correlates the switching ripple with the PV output power to maximize the output of the PV module. Compared to other MPPT methods, RCC has many advantages. Unlike the Perturb and Observe, RCC uses the ripple from the switch of the converter as a perturbation to disturb the duty ratio rather than using external perturbation [22]. Also, RCC has fast tracking speed and is not sensitive to
the parameters of the PV module [23]. However, the RCC proposed in [23] is based on a dc-dc converter with PWM control. In this thesis, the RCC has been adopted in the single-stage three-phase PV inverter with hysteresis current control.

The synchronous rotating reference frame has been used in the power control system. In the balanced three-phase system, the three-phase variables can be converted to two-phase variables. Through this way, the control system is simplified. The instantaneous real and reactive power can be easily calculated.

Since the proposed system is a grid-connected system, harmonics and current ripple produced by the inverter and PV system must be filtered by an LC filter to prevent them from entering the grid. However, resonance between the LC filter and transformer can be excited by the switch harmonics of the inverter. The resonance frequency between LC filter and transformer is hard to avoid by adjusting the switch frequency or selecting capacitance, because of variable switching frequency caused by hysteresis current control. Paralleling a resistor with the capacitor of LC filter can reduce the current harmonics, but it causes additional power loss [24]. The virtual resistance damping method can be implemented in the control system to dampen the resonance component without any additional power loss. This method has been present in numerous of papers [25] [26]. However, the virtual resistance damping method is implemented in the synchronously rotating reference frame to simplify overall control system design.

1.2 Thesis Outline

In this paper, a power control with RCC and active damping system is proposed for the three-phase single-stage grid-connected PV inverter and a local linear reactive power controller is investigated, and alternative methods of selecting the local linear control parameter are explored. The remainder of thesis is organized as follows:
Chapter 2 described background about the PV characteristics and hysteresis current control for inverters. In Chapter 3, the local linear reactive power controller and PV inverter control system are described. In Chapter 4, two simulations are developed and the results is provided. The local linear controller is demonstrated and its performance is assessed in the presence of PV output variability and the PV control system is tested and its results are assessed in the presence of irradiance variability. The initial experimental results and information are discussed in Chapter 5. Conclusions and avenues of future work are discussed in Chapter 6.
Chapter 2

Background

The PV array characteristics and hysteresis current controller will be introduced in this section.

2.1 Photovoltaic Array Characteristics

The modeling of PV arrays is used to describe and predict the characteristics of PV arrays. The PV array is composed of series and parallel connected PV cells. The equivalent circuit of PV cell is shown in Fig. 2.1

![Diagram of Basic Equivalent Circuit of PV Cell](image)

Figure 2.1: Basic equivalent circuit of PV cell
The basic equation [27] describing the behavior of a PV array is

\[ I = M \left[ I_{pv} - I_0 \left[ \exp \left( \frac{q(V_{pv} + R_s I_{M})}{a k T} \right) - 1 \right] - \frac{V_{pv}}{N} + \frac{R_s I_{M}}{R_p} \right] \]  \tag{2.1}

where \( I_{pv} \) is the light-generated current, \( V_{pv} \) is the output voltage of the PV array, \( I \) is the output current of the PV array, \( I_0 \) is the diode reverse saturation current, \( q \) is the electron charge, \( a \) is the diode ideality factor, \( k \) is the Boltzmann constant, \( T \) is the cell temperature, \( M \) is the numbers of cells in parallel, \( N \) is the numbers of cells in series, \( R_s \) is the series resistance and \( R_p \) is the parallel resistance. The light-generated current is determined by the irradiance and temperature as shown [28]:

\[ I_{pv} = [I_{pv,n} - K_I(T - T_n)] \frac{G}{G_n} \]  \tag{2.2}

where \( I_{pv,n} \) is the nominal light-generated current, \( T_n \) is the nominal cell temperature, \( G \) is the irradiance, \( G_n \) is the nominal irradiance, \( K_I \) is the short circuit current coefficient. The diode reverse saturation current is influenced by the temperature as shown [28]:

\[ I_0 = I_{0,n} \left( \frac{T_n}{T} \right)^3 \exp \left[ \frac{qE_g}{a k} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right] \]  \tag{2.3}

where

\[ I_{0,n} = \frac{I_{sc}}{\exp \left( \frac{qV_{oc}}{a k T} \right) - 1} \]  \tag{2.4}

\( I_{0,n} \) is the nominal diode reverse saturation current, \( E_g \) is the band-gap energy of the semiconductor, \( I_{sc} \) is the nominal short circuit current of PV cell and \( V_{oc} \) is the nominal open circuit voltage of PV cell. The P-V curve and I-V curve of a PV module are shown in Fig. 2.2 and Fig. 2.3. In Fig. 2.2, it can be seen that the output power of PV array is maximum only if the voltage of PV array equals that of \( v_{mpp} \) which is the voltage corresponding to the maximum power point (MPP). As the irradiance changes, the P-V curve is changed accordingly. The MPP will also shift as
the irradiance changes, as shown in Fig. 2.4. The PV array need be controlled by a MPPT system to extract maximum output power from it.
2.2 Hysteresis Current Controller

Hysteresis current controller is a means of controlling inverter which makes the output current follow the reference current. The hysteresis current controller compares the error between the measured inductor current $i_{nf}$ and the reference current $i_{nf}^*$ within the given boundaries to determine whether the top or the bottom switch will turn on. The equation of the switch signal is

$$
S_n = \begin{cases} 
1 & \text{if } i_{nf}^* - i_{nf} > h \\
-1 & \text{if } i_{nf}^* - i_{nf} < -h 
\end{cases}
$$

where $n$ can represent either $a$ phase, $b$ phase or $c$ phase, $i_{nf}$ is the inductor current of $n$ phase, $i_{nf}^*$ is the reference current of $n$ phase, $S_n$ is the switch signal and $h$ is the hysteresis band. For one branch of three-phase inverter, either the top switch or bottom switch will turn on. One branch of three-phase inverter is shown in Fig. 2.5. The top switch will turn on when $S_n$ is equal to 1 and the bottom switch will turn
Figure 2.5: One branch of three phase inverter

Figure 2.6: Hysteresis current control

on when $S_n$ is equal to $-1$. The switch state does not change while the current error remains within the hysteresis band. As shown in Fig. 2.6, the current will be keep in the hysteresis band.
Chapter 3

Control of The Proposed System

The whole proposed control system is shown in Fig. 3.1. It can been seen that the control system contain two parts, namely, local linear reactive power control and PV inverter control. The reactive power control is used to determine how much reactive power should be injected into the grid corresponding to certain real output power. The PV inverter control is used to control the PV inverter to maximize the PV output power and inject the reactive output power into the grid.

3.1 Reactive Power Control

Herein, a local linear controller [29] is studied to allow a PV inverter to adjust its reactive power output in response to fluctuations in real power. The controller can be expressed as

\[ Q = Q^* + \beta(P^* - P) \]  

(3.1)

where \( P \) and \( Q \) are the real and reactive output power of PV inverter, respectively, \( P^* \) and \( Q^* \) are the real and reactive reference power, respectively, and \( \beta \) is a control parameter called the substitution rate. The objective of this controller is to mitigate
against system voltage variation caused by fluctuating PV real output power. The method of choosing the control parameter $\beta$ is studied herein.

All else being equal, the system voltages can be expressed as a function of PV real and reactive output power:

$$ V = f(P, Q) $$  \hspace{1cm} \text{(3.2)}

where $V$ is a vector containing bus voltage magnitudes. According to the method of selecting the substitution factor (described below), $V$ may contain either the per phase or phase average bus voltage magnitudes of either the local bus or all of the system buses. Taylor series expansion of (3.2) about the operating point $(P^*, Q^*)$
yields
\[
\Delta V \approx \alpha_P \Delta P + \alpha_Q \Delta Q
\] (3.3)
where
\[
\Delta V = V - V^* = f(P, Q) - f(P^*, Q^*)
\] (3.4)
\[
\Delta P = P - P^*
\] (3.5)
\[
\Delta Q = Q - Q^*
\] (3.6)
\[
\alpha_P = \frac{\partial f}{\partial P}
\] (3.7)
\[
\alpha_Q = \frac{\partial f}{\partial Q}
\] (3.8)
The partial derivative terms $\alpha_P$ and $\alpha_Q$ are called sensitivity factors, and these can be estimated using small perturbations about the operating point:
\[
\alpha_P \approx \frac{(V(P^* + \delta P, Q^*) - V^*)}{\delta P}
\] (3.9)
\[
\alpha_Q \approx \frac{(V(P^*, Q^* + \delta Q) - V^*)}{\delta Q}
\] (3.10)
where $\delta P$ and $\delta Q$ are small real and reactive power perturbations, respectively.
By substituting the control law (3.1) into (3.3), the response of the system voltages to a perturbation of real output power can be approximated as
\[
\Delta V = (\alpha_P - \beta \alpha_Q) \Delta P.
\] (3.11)
It can be seen that choice of the substitution rate $\beta$ can influence the response of the system voltages to output power fluctuations. There are two primary methods of selecting $\beta$ that are considered herein. These two methods are discussed below. Each of these methods can be applied on a per phase or on a phase average basis, and each
of these methods can be applied to only the local bus voltage or to all of the system bus voltages.

3.1.1 Sensitivity Minimization vs. Violation Optimization

The goal of sensitivity minimization method is to minimize the response of the bus voltages under consideration to output real power perturbations. From (3.11), this can be accomplished by making

$$\alpha_P - \beta \alpha_Q = 0.$$  \hfill (3.12)

In the general case, this cannot be achieved. However, the least squares solution is given by

$$\beta = \alpha_q^\dagger \alpha_P.$$  \hfill (3.13)

Recognizing that the goal of rendering the system voltages insensitive to output power perturbations expressed in (3.12) is not generally possible, the goal of the violation optimization method is to select \( \beta \) to maximize the magnitude of real power output perturbation for which none of the considered bus voltages leave its acceptable range. For any given bus, the bus voltage magnitude \( V \) is required to fall within a range:

$$V_l \leq V \leq V_u$$ \hfill (3.14)

where \( V_l \) is the lower limit voltage and \( V_u \) is the upper limit voltage. It is assumed that each bus voltage satisfies this requirement at the operating condition \((P^*, Q^*)\). This corresponds to a requirement on the deviation of each bus voltage magnitude:

$$\Delta V_l \leq \Delta V \leq \Delta V_u$$ \hfill (3.15)
where

\[ \Delta V_l = V_l - V^* \]  
\[ \Delta V_u = V_u - V^*. \]

(3.16)  
(3.17)

Combining (3.11) with (3.15) for each bus voltage under consideration yields the violation optimization method of selecting \( \beta \):

\[
\beta = \arg \max |\Delta P|
\]

such that \( \Delta V_l \leq (\alpha_P - \beta \alpha_Q) \Delta P \leq \Delta V_u. \)

(3.18)

### 3.1.2 Per Phase vs. Average Phase

The methods described above for selecting \( \beta \) can be applied using the magnitude of the bus voltages of each phase individually or using the average of the three-phases. Suppose the phase voltage magnitudes of bus \( m \) are \( V_{am}, V_{bm}, \) and \( V_{cm} \). If the per phase method is used, then bus \( m \) is represented in the voltage vector defined in (3.2) by the three elements \([V_{am} V_{bm} V_{cm}]^T\). If the average phase method is used, then bus \( m \) is represented by the single element \( \bar{V}_m = (V_{am} + V_{bm} + V_{cm})/3 \). The bus is similarly represented in the sensitivity factor vectors \( \alpha_P \) and \( \alpha_Q \).

### 3.1.3 Local Bus Voltage vs. Global Bus Voltages

The methods described above for selecting \( \beta \) can be applied to either the local bus voltage (i.e., the bus at which the PV inverter is located) or to all of the bus voltages in the system. Suppose there are \( M \) buses and the PV inverter is located at bus \( n \). If the local bus voltage method is used, only bus \( n \) is represented in the bus voltage vector \( V \) defined in (3.2). If the global bus voltages method is used, all of the system buses are represented in the bus voltage vector. The sensitivity factor vectors \( \alpha_P \) and
\( \alpha_Q \) are similarly affected by the choice to represent only the local bus or to represent all of the system buses.

### 3.1.4 Summary

Without loss of generality, it is assumed that the buses studied herein are three-phase buses. The system is not required to be balanced, and the method can readily be generalized to handle one- and two-phase buses as well. If the per phase and local bus voltage methods are used, the bus voltage vector is defined as

\[
V = [V_{an} \ V_{bn} \ V_{cn}]^T
\]  

(3.19)

and the bus voltage vector contains 3 elements. If the average phase and local bus voltage methods are used, the bus voltage vector, which is actually a scalar, is defined as

\[
V = \bar{V}_n. \tag{3.20}
\]

If the per phase and global bus voltages methods are used, the bus voltage vector is defined as

\[
V = [V_{a1} \ V_{b1} \ V_{c1} \ V_{a2} \ V_{b2} \ V_{c2} \ldots \ V_{aN} \ V_{bN} \ V_{cN}]^T
\]  

(3.21)

and the bus voltage vector contains \( 3N \) elements. If the average phase and global bus voltage methods are used, the bus voltage vector is defined as

\[
V = [\bar{V}_1 \ \bar{V}_2 \ \ldots \ \bar{V}_N]^T
\]  

(3.22)

and the bus voltage vector contains \( N \) elements. The sensitivity factor vectors \( \alpha_P \) and \( \alpha_Q \) are defined in (3.7) and (3.8) and are affected by the choice of \( V \).
3.2 Control of the PV Inverter System

The PV inverter control system consists of four parts, namely the MPPT control, the power control, the phase lock loop (PLL) and the virtual resistance damping system. The MPPT control is used to control the array to deliver the maximum power to the grid. The power control is designed to regulate the reactive power injected into the grid. In the PLL section, the grid frequency and angle are estimated from the capacitor voltage. The virtual resistance damping system is used to reduce the resonance component from the LC filter and transformer.

3.2.1 Ripple Correlation Control

RCC is used to find the maximum power point under a given temperature and irradiance. The MPPT control equation for the dc-dc boost converter is proposed in [23]. It is shown as follows

\[ d = -k_m \int \frac{dP_{out}}{dt} \frac{dV_{pv}}{dt} dt = -k_m \int \frac{dP_{out}}{dV_{pv}} \left( \frac{dV_{pv}}{dt} \right)^2 dt \]  

(3.23)

where \( P_{out} \) is the output power of PV array which is equal to \( V_{pv} I \), \( V_{pv} \) is the array voltage, \( k_m \) is a positive gain and \( d \) is the switch duty cycle. To implement the RCC into inverter hysteresis current control, the reference current \( i^* \) is used instead of switch duty cycle \( d \). The equation (3.23) of RCC for hysteresis current control is

\[ i^* = -k_m \int \frac{dP_{out}}{dt} \frac{dV_{pv}}{dt} dt = -k_m \int \frac{dP_{out}}{dV_{pv}} \left( \frac{dV_{pv}}{dt} \right)^2 dt \]  

(3.24)

The time derivative of the equation (3.24) is

\[ \frac{di^*}{dt} = -k_m \frac{dP_{out}}{dV_{pv}} \left( \frac{dV_{pv}}{dt} \right)^2 \]  

(3.25)
The \((\frac{dV_{pv}}{dt})^2\) is positive, because the voltage is always changed by the active switch [30]. If \(V_{pv} < v_{mpp}\), \(\frac{dP_{out}}{dV_{pv}}\) will be positive, as shown in Fig. 2.2. The parameter \(k_m\) is positive, so \(\frac{di^*}{dt} < 0\). From Fig. 2.3, it can be seen that the decreasing \(i^*\) will cause \(V_{pv}\) to increase until it reaches the \(v_{mpp}\). Similarly, if \(V_{pv} > v_{mpp}\), \(\frac{dP_{out}}{dV_{pv}}\) will be negative. The \(i^*\) will increase, which will cause \(V_{pv}\) to decrease until it reaches the \(v_{mpp}\). The output power reference \(P_{ref}\), used by the power control, is the product of \(i^*\) and the output voltage of the PV module. With the proper cutoff frequency, a high-pass filter can be used to approximate the time derivative. The RCC scheme diagram is illustrated in Fig. 3.2.

![Diagram of RCC](image)

Figure 3.2: Diagram of RCC

### 3.2.2 Power Control

From Section 3.1, we have

\[
S^* = P_{ref} + j(Q^* + \beta(P^* - P_{ref}))
\] (3.26)

where \(S^*\) is the reference power from the local linear controller. However, \(S^*\) is the power we want to feed into grid rather than the reference output power of inverter, because there is a power offset \(\Delta S_g\) caused by the capacitor of the LC filter and virtual resistance damping. The method of obtaining power offset \(\Delta S_g\) is described
in Section 3.2.4. By adding the offset power to the reference power, we have

\[ P^*_g = P_{ref} + \Delta P_g \] (3.27)

\[ Q^*_g = (Q^* + \beta(P^* - P_{ref})) + \Delta Q_g \] (3.28)

where \( P^*_g \) and \( Q^*_g \) are the fundamental real and reactive reference power, respectively. The synchronous rotating reference frame is introduced to simplify the control system. Reference frame theory is used to transform the three-phase variables into the synchronous rotating reference frame. The formulation [31] is

\[ \mathbf{f}^e_{qd0} = \mathbf{K}^e_s \mathbf{f}_{abcs} \] (3.29)

or

\[ \mathbf{f}^e_{abcs} = (\mathbf{K}^e_s)^{-1} \mathbf{f}_{qd0} \] (3.30)

where

\[
\mathbf{K}^e_s = \frac{2}{3}
\begin{bmatrix}
\cos(\theta_e) & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\
\sin(\theta_e) & \sin(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\] (3.31)

\[ \mathbf{f}^e_{qd0} = \begin{bmatrix} f^e_{qs} & f^e_{ds} & f^e_{0s} \end{bmatrix}^T \] (3.32)

\[ \mathbf{f}^e_{abcs} = \begin{bmatrix} f^e_{as} & f^e_{bs} & f^e_{cs} \end{bmatrix}^T \] (3.33)

where \( f \) can represent either voltage or current. \( \theta_e \) is the angle associated with the fundamental frequency of the grid voltage. In a balanced steady-state condition [31], the phase relationship between the \( a \) phase variable and synchronous rotating reference variables is

\[ \sqrt{2} \tilde{F}^e_{as} = f^e_{qs} - j f^e_{ds} \] (3.34)
where $\tilde{F}_{as}$ is a phasor which can be either voltage or current. We know

$$S_g^* = 3\tilde{V}_{af}\tilde{I}_{af,r}^*$$

(3.35)

where $\tilde{V}_{af}$ is a phase capacitor voltage, $\tilde{I}_{af,r}^*$ is the conjugate of a phase inductor reference current $\tilde{I}_{af,r}$ of LC filter. Combining equations (3.34) and (3.35), we obtain

$$P_g^* + jQ_g^* = 3\left(\frac{v_{qf}^e - jv_{df}^e}{\sqrt{2}}\right)\left(\frac{i_{qf,r}^e + ji_{df,r}^e}{\sqrt{2}}\right)$$

(3.36)

that is

$$P_g^* = \frac{3}{2}(v_{qf}^e i_{qf,r}^e + v_{df}^e i_{df,r}^e)$$

(3.37)

$$Q_g^* = \frac{3}{2}(v_{qf}^e i_{df,r}^e - v_{df}^e i_{qf,r}^e)$$

(3.38)

In order to obtain the fundamental component of inductor reference current, the $v_{qf}^e$ and $v_{df}^e$ need to be filtered by a lower-pass filter. So, the equations for power control are

$$\overline{v_{qf,r}^e} = \frac{2(v_{qf}^e P_g^* - v_{df}^e Q_g^*)}{3(v_{qf}^{e2} + v_{df}^{e2})}$$

(3.39)

$$\overline{v_{df,r}^e} = \frac{2(v_{df}^e P_g^* + v_{qf}^e Q_g^*)}{3(v_{qf}^{e2} + v_{df}^{e2})}$$

(3.40)

where $\overline{v_{qf}^e}$ and $\overline{v_{df}^e}$ are the fundamental component of capacitor voltage, $\overline{v_{qf,r}^e}$ and $\overline{v_{df,r}^e}$ are the fundamental reference current.

### 3.2.3 Phase Lock Loop

To transfer three-phase variables of stationary circuit elements to the synchronously rotating reference frame, the information about grid angular frequency $\omega_e$ and grid phase $\theta_e$ is needed. A PLL is used to extract the grid angle and phase information from the grid. In this thesis, a conventional PLL [32] has been adopted. In a balanced
condition, we have

\[
\begin{bmatrix}
  v_{af} \\
  v_{bf} \\
  v_{cf}
\end{bmatrix} =
\begin{bmatrix}
  \sqrt{2}v_s \cos(\omega_e t) \\
  \sqrt{2}v_s \cos(\omega_e t - \frac{2}{3}\pi) \\
  \sqrt{2}v_s \cos(\omega_e t + \frac{2}{3}\pi)
\end{bmatrix}
\]  \quad \text{(3.41)}

where \(v_s\) is the rms value of line-to-neutral capacitor voltage and \(v_{af}, v_{bf}\) and \(v_{cf}\) are the line-to-neutral capacitor voltage of \(a\) phase, \(b\) phase and \(c\) phase. Substituting (3.41) into (3.29) yields

\[
v_{df}^e = -\sqrt{2}v_s \sin(\omega_e - \hat{\omega}_e)t
\]  \quad \text{(3.42)}

The control equation for PLL is

\[
\hat{\omega}_e = K_p(0 - v_{df}^e) + K_i \int (0 - v_{df}^e)dt
\]  \quad \text{(3.43)}

where \(K_p\) is proportional gain, \(K_i\) is integral gain and \(\hat{\omega}_e\) is the estimated angular frequency. This control system will drive \(v_{df}^e\) to zero. Hence, \(\hat{\omega}_e\) is equal to \(\omega_e\) at the steady state. As a result, \(\omega_e\) can be estimated by the capacitor voltage. The structure of PLL is shown in Fig. 3.3

![Diagram of PLL method](image)

Figure 3.3: Diagram of PLL method
3.2.4 Virtual Resistance Damping System

In order to reduce the injection of the harmonic current into the grid, the harmonics produced by the three-phase inverter must be filtered. Compared with the L filters, the LC filters have better performance, lower inductance and smaller size. However, because the three phase inverter is a grid-connected system, the LC filter connects with the transformer to form an LCL filter. The harmonics in the inductor current has a large range of frequency because of the hysteresis current control. Because the grid and transformer inductance normally are unknown, it is difficult to select an LC filter whose resonant frequency is out of the range of current harmonics. So, the current oscillation resulting from the LC filter and transformer must be damped. The virtual resistor and capacitor are used to dampen the oscillation and avoid additional power loss at the same time. Because the inductor current is the current that is controlled directly by the hysteresis current controller, the inverter and the inductor can be considered as a current source. The equivalent circuit of the LCL filter is shown in Fig. 3.4. The transfer function for the inductor current and the transformer current is given by

\[
\frac{I_f}{I_n} = \frac{1}{s^2 L_n C_f + 1}
\]  

(3.44)

After paralleling a series-connected capacitor and resistor with the capacitor of the LC filter, the equivalent circuit is shown in Fig. 3.5. Then, the transfer function
The bode plot for the different transfer functions is given in Fig. 3.7. It can be seen that the maximum magnitude of the transfer function has been reduced a lot with paralleling a series-connected capacitor and resistor. So, the virtual capacitor and resistor can be added into the control system to dampen the resonant current. The damping currents $i_{qk}^e$ and $i_{dk}^e$ are given by the below functions

$$i_{qk}^e = \frac{v_{qf}^e - v_{qk}^e}{R_k}$$  \hspace{1cm} (3.46)

$$i_{dk}^e = \frac{v_{df}^e - v_{dk}^e}{R_k}$$  \hspace{1cm} (3.47)

$$C_k \frac{dv_{qk}^e}{dt} = i_{qk}^e - \hat{\omega}_e C_k v_{dk}^e$$  \hspace{1cm} (3.48)

$$C_k \frac{dv_{dk}^e}{dt} = i_{dk}^e + \hat{\omega}_e C_k v_{qk}^e$$  \hspace{1cm} (3.49)

where $v_{qk}^e$ and $v_{dk}^e$ are the virtual capacitor voltages in the rotating reference frame.

The damping current are subtracted by the reference currents $\bar{i}_{qf,r}^e$ and $\bar{i}_{df,r}^e$ to damp the resonance components. However, the virtual resistance damping and the capacitor of the LC filter can cause an offset in the output power of the inverter. To compensate this offset, the fundamental component of offset power $\Delta S_g$ needs to be added to the
reference power. The fundamental component of offset power $\Delta S_g$ can be calculated from capacitor voltage and branch impedance as in the following equation

$$\Delta S_g = 3V_{as}\left[\frac{V_{as}}{(\frac{1}{j\hat{\omega}C_k} + \frac{1}{j\hat{\omega}C_f}) \parallel (\frac{1}{j\hat{\omega}C_k} + \frac{1}{j\hat{\omega}C_f})} \right]^*$$

(3.50)

where $V_{as}$ is the fundamental component of the capacitor voltage. Combining equations (3.34) and (3.50), we have

$$\Delta P_g = \frac{3(v_{af}^2 + v_{df}^2)\hat{\omega}^2C_k^2R_k}{2(\hat{\omega}^2C_k^2R_k^2 + 1)}$$

(3.51)

$$\Delta Q_g = -\frac{3(v_{af}^2 + v_{df}^2)}{2}(\hat{\omega}C_f + \frac{\hat{\omega}C_k}{\hat{\omega}^2C_k^2R_k^2 + 1})$$

(3.52)

The diagram of the virtual resistance damping method is shown in Fig. 3.6
Figure 3.7: Bode plot of transfer functions with and without damping system
Chapter 4

Simulation Results

4.1 Simulation Results of Local Linear Reactive Power Control

In order to investigate the performance of the PV inverter reactive power control with different methods of choosing the substitution rate $\beta$, a simple five-bus distribution system is studied. The system is shown in Figure 4.1. The base voltage of the system is 4.16 kV, and the source at bus 1 is at 1.05 pu with a series impedance of $0.01 + j0.08$ pu with a base power of 1.4 MVA. The unbalanced, per-unit-length series reactance and resistance matrices for lines 1-2 and 2-4 are

$$X = \begin{bmatrix}
1.0179 & 0.5017 & 0.4236 \\
0.5017 & 1.0478 & 0.3849 \\
0.4236 & 0.3849 & 1.0348 \\
0.3465 & 0.1560 & 0.1580 \\
0.1560 & 0.3375 & 0.1535 \\
0.1580 & 0.1535 & 0.3414
\end{bmatrix} \Omega/\text{mile} \quad (4.1)$$

$$R = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} \Omega/\text{mile} \quad (4.2)$$
and the unbalanced, per-unit-length reactance and resistance matrices for lines 2-3 and 4-5 are

\[
X = \begin{bmatrix}
1.1814 & 0.4236 & 0.5071 \\
0.4236 & 1.1983 & 0.3849 \\
0.5071 & 0.3849 & 1.2112
\end{bmatrix} \text{Ω/mile} \quad (4.3)
\]

\[
R = \begin{bmatrix}
0.7526 & 0.1580 & 0.1560 \\
0.1580 & 0.7475 & 0.1535 \\
0.1560 & 0.1535 & 0.7436
\end{bmatrix} \text{Ω/mile.} \quad (4.4)
\]

These line parameters are derived from the IEEE 13-bus test feeder described in [33]. The PV inverter operating point is 800 kW and 0 kvar. The upper and lower limits of each bus voltage magnitude are 126 V and 118 V, respectively, with respect to a 120-V base. The sensitivity factors for each phase of each bus at this operating point are shown in Table 4.1. It can be seen that the sensitivity factors between each phase of a bus are similar, but they differ significantly between buses. Accordingly, the substitution rates \( \beta \) calculated by each of the different methods are shown in Table 4.2.

The system is simulated for 15 minutes using PV output power derived from the 1-s global horizontal irradiance data collected at the National Renewable Energy
Laboratory Solar Measurement Grid in Oahu, Hawaii. In particular, data collected at the location DH3 on March 1, 2011 between 11:00 am and 11:15 am was scaled to provide a mean output power during this interval that corresponds to the operating point of 800 kW. The use of 1-s data is appropriate because MPPT algorithms are capable of converging to the correct maximum power point very quickly [34]. The
Table 4.3: System Voltage Performance Metrics

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum Deviation (mV)</th>
<th>Mean Deviation (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bus 1</td>
<td>Bus 2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>Time of Deviation (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bus 1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

PV output power is shown in Figure 4.2. It can be seen that the output power can fluctuate rapidly within this interval of time (between $0.33P^*$ and $1.6P^*$), and these fluctuations occur too quickly for traditional distribution system voltage regulation equipment to respond.

To study the effect of the PV reactive power controller on distribution system voltages, several performance metrics are employed. First, the maximum deviation for a bus is the maximum deviation from the allowable voltage range experienced by the phase-average voltage magnitude. The mean deviation for a bus is the mean over
the 15-minute interval of the phase-average voltage magnitude deviation. Both of the deviation metrics are calculated on a 120-V base. The time of deviation of a bus is the duration of deviations in the phase-average voltage magnitude deviation. The values of these metrics, which are all calculate on a phase-average basis, for the different methods of calculating $\beta$ are shown in Table 4.3. In this table, Case 0 represents the case in which no reactive power compensation is performed.

It can be seen that without the local linear reactive power controller, the PV output variations cause significant deviations in the local bus voltage. In particular, the maximum deviation of bus 5 is approximately 1.4 V. It can also be seen that bus 3 experiences voltage deviations due to the variation (maximum deviation of around 0.4 V). In total, the bus voltages of the system are outside of the acceptable range for approximately 30% of the duration of the study.
When the local controller is used with any of the methods of selecting the substitution rate $\beta$, the local bus no longer exhibits voltage deviations during the study. In most cases, the maximum and mean deviations and the time of deviation of bus 3 are reduced by application of the reactive power controller. However, in cases 1, 2, and 5, the maximum deviation and time of deviation of bus 3 actually increase. These cases are each cases in which only the local bus voltage is used to calculate the substitution rate. This suggests that it is important to solve the problem globally rather than locally. The case in which the performance metrics improved the most is case 8, which uses the violation optimization method on a global, per-phase basis. In this case, the maximum deviation of bus 3 is reduced by 86%, the mean deviation is reduced by more than 99%, and the time of deviation is reduced by 96%. The phase-average voltage and per phase voltage magnitude of the local bus without the local controller and with the controller (using case 8) is shown in Figure 4.3. The phase-average and per phase voltage magnitude of bus 3 is shown in Figure 4.4.
Figure 4.3: voltage magnitude at local bus.
Figure 4.4: voltage magnitude at bus 3.
Table 4.4: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substitution rate</td>
<td>$\beta = 0.3$</td>
</tr>
<tr>
<td>Proportional gain of PLL</td>
<td>$K_p = 1$</td>
</tr>
<tr>
<td>Integral gain of PLL</td>
<td>$K_i = 0.1$</td>
</tr>
<tr>
<td>Inductance of LC filter</td>
<td>$L_f = 0.276$ mH</td>
</tr>
<tr>
<td>Capacitance of LC filter</td>
<td>$C_f = 24$ µF</td>
</tr>
<tr>
<td>Transformer inductance</td>
<td>$L_n = 76.338$ µH</td>
</tr>
<tr>
<td>Grid line-to-line rms voltage</td>
<td>$V_g = 120$ V</td>
</tr>
<tr>
<td>Hysteresis band</td>
<td>$h = 4.75$ A</td>
</tr>
<tr>
<td>Virtual capacitance</td>
<td>$C_k = 63.246$ µF</td>
</tr>
<tr>
<td>Virtual resistance</td>
<td>$R_k = 3$ Ω</td>
</tr>
<tr>
<td>Time constant of lower pass filter</td>
<td>$\tau_d = 3.1831$ ms</td>
</tr>
</tbody>
</table>

4.2 Simulation Results of PV Inverter Systems

In order to examine the characteristics of the proposed PV inverter control system, a simulation model is developed.

4.2.1 Simulation Results With Constant Power Supply

To test the performance of the active damping, a simulation model without the PV module and RCC is developed. A dc power source take the place of the PV module. The voltage of the dc power supply is 235 V. $P^*$ is 1000 W and $P_{ref}$ is 7200 W. The characteristics and parameters of the simulation are listed in Table 4.4. Fig. 4.5 and Fig. 4.6 illustrate the simulated waveforms of the control system without and with the virtual resistance damping, respectively.
Figure 4.5: Simulation results of currents and voltage without damping system
Figure 4.6: Simulation results of currents and voltage with damping system
It can been seen that without the virtual resistance damping system, the maximum ripple of transformer current is larger than 80%. Comparing Fig. 4.6 with Fig. 4.5, the transformer current with virtual resistance damping system has fewer ripples and harmonics than the one without. And the capacitor voltage in Fig. 4.6 is also better than in Fig. 4.5. It can be seen that the virtual resistance damping system significantly reduces the oscillations result from resonance of the LC filter and transformer. Fig. 4.7 shows the oscillations and ripple in the real and reactive output power also be reduced.
4.2.2 Simulation results of whole PV inverter system

A simulation has been developed to investigate the characteristics of PV inverter system. The parameters of PV cell listed in Table 4.5 are derived from [28]. The rest of the parameters are the same as the parameters in Table 4.4. Fig. 4.8 shows that the output power of PV module stay at the MPP when the irradiance is varying, and the ripple of reference power $P_{ref}$ is less than 3.4%. Fig. 4.8 shows the waveforms of
Table 4.5: PV and RCC Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode ideally constant</td>
<td>( a = 1.3 )</td>
</tr>
<tr>
<td>Numbers of cells in parallel</td>
<td>( M = 4 )</td>
</tr>
<tr>
<td>Numbers of cells in series</td>
<td>( N = 486 )</td>
</tr>
<tr>
<td>Cell temperature</td>
<td>( T = 300 \text{ K} )</td>
</tr>
<tr>
<td>Semiconductor band-gap energy</td>
<td>( E_g = 1.12 \text{ eV} )</td>
</tr>
<tr>
<td>Short circuit current coefficient</td>
<td>( K_I = 0.0032 \text{ A/K} )</td>
</tr>
<tr>
<td>Short circuit current of PV cell</td>
<td>( I_{sc} = 8.21 \text{ A} )</td>
</tr>
<tr>
<td>Open circuit voltage of PV cell</td>
<td>( V_{oc} = 0.609259 \text{ V} )</td>
</tr>
<tr>
<td>Parallel resistance of PV cell</td>
<td>( R_p = 7.692685 \text{ Ω} )</td>
</tr>
<tr>
<td>Series resistance of PV cell</td>
<td>( R_s = 0.00409259 \text{ Ω} )</td>
</tr>
<tr>
<td>RCC gain</td>
<td>( k_m = 2 \times 10^{-8} )</td>
</tr>
<tr>
<td>Time constant of HPF of RCC</td>
<td>( \tau_r = 1.5915494 \text{ µs} )</td>
</tr>
</tbody>
</table>

the real power and reactive power following the change of the irradiance. As shown in Fig. 4.9, from 0.1 s to 0.2 s, the irradiance decreases from 1000 W/m\(^2\) to 500 W/m\(^2\), at the same time, the real output power decreases from 7250 W to 3600 W. To mitigate distribution system voltage fluctuations, the reactive power is increased from -1850 var to -780 var.

Fig. 4.9 shows the capacitor voltage is pretty stable and the transformer current has small ripple and no additional distortion when irradiance is decreasing.
Figure 4.8: Simulation results of PQ injection
Figure 4.9: Simulation results of currents and voltage
Chapter 5

Experiments

5.1 Experimental Results

In order to examine the proposed control system, a prototype has been developed. A three-phase grid-connected inverter has been built in the laboratory. As shown in the Fig. 5.1, Fig. 5.2 and Fig. 5.3, the prototype is based on the simulation of the PV inverter with a dc power supply. The inductance and capacitance of the LC filter are the same as in the simulation. The phase-to-phase grid voltage is 125 V. The capacitance of the capacitor connected to the dc power supply is 680 μF. The digital controller has been developed using a TMS320 microcontroller by Texas Instruments.

To test the performance of the hysteresis current control, the three-phase inverter is connected with a load bank. The inverter dc side voltage is 250 V. The rms value of the reference current is 40 A. The result of the hysteresis current control is shown in Fig. 5.4. For a resistor load, the line-to-neutral voltage has the same phase angle as the current. Therefore, inductor current $i_a$ is lagging capacitor voltage $v_{ab}$ by 30 degrees.
From the Fig. 5.1, it can be found the capacitors of the LC filter are $\Delta$-connected. Therefore, there are no neutral point in the circuit. However, $v_{qf}^c$ and $v_{df}^c$ are needed.
for the power control and PLL. The line-to-line capacitor voltage can easily be measured. For the capacitor voltages, there are two equations as follow

\[
\begin{bmatrix}
  v_{qf}^e \\
  v_{df}^e 
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
  \cos \theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\
  \sin \theta_e & \sin(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) 
\end{bmatrix} \begin{bmatrix}
  v_{af} \\
  v_{bf} \\
  v_{cf} 
\end{bmatrix} \tag{5.1}
\]

and

\[
0 = \frac{2}{3} \begin{bmatrix}
  \cos \theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\
  \sin \theta_e & \sin(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) 
\end{bmatrix} \begin{bmatrix}
  v_{bf} \\
  v_{bf} \\
  v_{bf} 
\end{bmatrix} \tag{5.2}
\]

subtracting (5.1) from (5.2)

\[
\begin{bmatrix}
  v_{qf}^e \\
  v_{df}^e 
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
  \cos \theta_e & \cos(\theta_e + \frac{2\pi}{3}) \\
  \sin \theta_e & \sin(\theta_e + \frac{2\pi}{3}) 
\end{bmatrix} \begin{bmatrix}
  v_{abf} \\
  v_{cbf} 
\end{bmatrix} \tag{5.3}
\]
Figure 5.4: Experimental results of hysteresis current control

where $v_{abf}$ is equal to $v_{af} - v_{bf}$ and $v_{cbf}$ is equal to $v_{cf} - v_{bf}$.

There are two interrupt service routines in the code, which are the fast one and the slow one. The fast one is used to be a hysteresis controller to compare the inductor current with the reference current. The PLL and power control are implemented in the slow interrupt. To get the best performance, the hysteresis current control needs to be run as fast as possible. The calculation of trigonometric functions is a time consuming process. If trigonometric functions are calculated directly, six
trigonometric functions, which are \( \cos \theta_e, \cos(\theta_e \pm \frac{2\pi}{3}) \), \( \sin \theta_e \) and \( \sin(\theta_e \pm \frac{2\pi}{3}) \), need to be calculated in each slow interrupt. Instead of calculating trigonometric function each time for different values, \( \sin(\theta_e \pm \frac{2\pi}{3}) \) and \( \cos(\theta_e \pm \frac{2\pi}{3}) \) can be calculated from \( \sin \theta_e \) and \( \cos \theta_e \) by sum and difference formulas. The equations are

\[
\cos(\theta_e \pm \frac{2\pi}{3}) = -\frac{1}{2} \cos \theta_e \mp \frac{\sqrt{3}}{2} \sin \theta_e \tag{5.4}
\]

\[
\sin(\theta_e \pm \frac{2\pi}{3}) = -\frac{1}{2} \sin \theta_e \pm \frac{\sqrt{3}}{2} \cos \theta_e. \tag{5.5}
\]

So, only two trigonometric functions need to be calculated each time.

In order to ensure the PLL works properly, a code, shown below, has been written in the microcontroller.

```c
if(thetae > PIoverthree && thetae < fourPIoverthree)
{
GpioDataRegs.GPACLEAR.bit.GPIO29 = 1;
}
else
{
GpioDataRegs.GPASET.bit.GPIO29 = 1;
}
```

The indicator of microcontroller will output 0 V when \( \frac{\pi}{3} < \theta_e < \frac{4\pi}{3} \), otherwise the output is 3.3 V. The experimental result of PLL is shown in Fig. 5.5. It can been seen that PLL works satisfactorily.

To run the experiment in the lab, two power sources need to be turned on. If the ac side is energized first, the three-phase inverter will work as an three-phase full-bridge rectifier, which may cause damage to the circuit. Therefore, the dc power supply needs to be turned on first and raised to a certain level to prevent this damage.
For the three-phase full-bridge rectifier, the maximum output voltage is

\[ v_{dc} = \frac{6V_0}{\pi} \sin\left(\frac{\pi}{3}\right) \]  

(5.6)

where \( V_0 \) is the magnitude of the line-to-neutral voltage of grid. So, the dc power supply need to be turned on first and the voltage must greater than 169 V. The experimental results of the grid-connected inverter with PLL and hysteresis control is shown in Fig. 5.6 and Fig. 5.7. The voltage of dc source is 200 V, and the line-to-line grid voltage is 125 V. In both figures, the reference current has the same phase angle as the line-to-neutral voltage. So, there is 30 degrees phase shift between the line-to-line voltage and current. In Fig. 5.6, the current ripple is large, since the output signal of the current sensor lags 7 \( \mu \)s behind the measured current and the rate of change of current is the largest when the current is close to zero.
Figure 5.6: Experimental results of injection current 1
Figure 5.7: Experimental results of injection current 2
Chapter 6

Conclusion and Future Work

6.1 Conclusion

At first, a local linear controller that substitutes reactive power output for real power output to mitigate against voltage fluctuations due to PV output variability is presented. Several methods of calculating the control parameter for this controller are described, including sensitivity minimization and violation optimization methods, which can be applied on a local or global basis and on a per-phase or phase-average basis. Secondly, a three-phase grid-connected single-stage PV system with MPPT and power control is described. A method of reducing the current harmonic caused by resonance of the LC filter and transformer is presented. The local controller is examined using a five-bus distribution system, and it is found that the local linear controller is effective at mitigating voltage violations. Furthermore, using the violation optimization method on a global, per-phase basis yields the best improvement in distribution system voltages. The power control of PV systems is examined using three-phase single-stage PV inverter system. The simulation results of the MPPT, power control and damping system show good performance and stability under rapid change of irradiance.
6.2 Future Work

In the future, this method will be examined for larger distribution systems, including systems with multiple PV sources. Interaction of the local linear controller with the power controller of the PV inverter will be studied. Coordination of this method of reacting to short-term variability with longer term problems, such as the dispatch of inverter reactive power for distribution system power control, will be examined.

For real and reactive power control of the PV inverter, interaction of the damping system with the switching frequency of hysteresis current controller will be studied. The RCC of PV inverter system with step irradiance change and load change will be examined. The fixed-frequency hysteresis current control will be implemented in the system to improve the performance of the RCC of PV inverter system. The control system under the unbalanced three-phase grid voltages could be studied. The hysteresis current control with switching time prediction can be implemented to compensate the time delay between the output signal of a current sensor and measured current. The average model of a PV inverter will be developed and connected with the simulation of local linear control to examine the whole systems performance.


Vita

Author’s Name: Xiao Liu

Education: Yangtze University, B.S. awarded June 2009

Professional Position: Research Assistant

Publications: