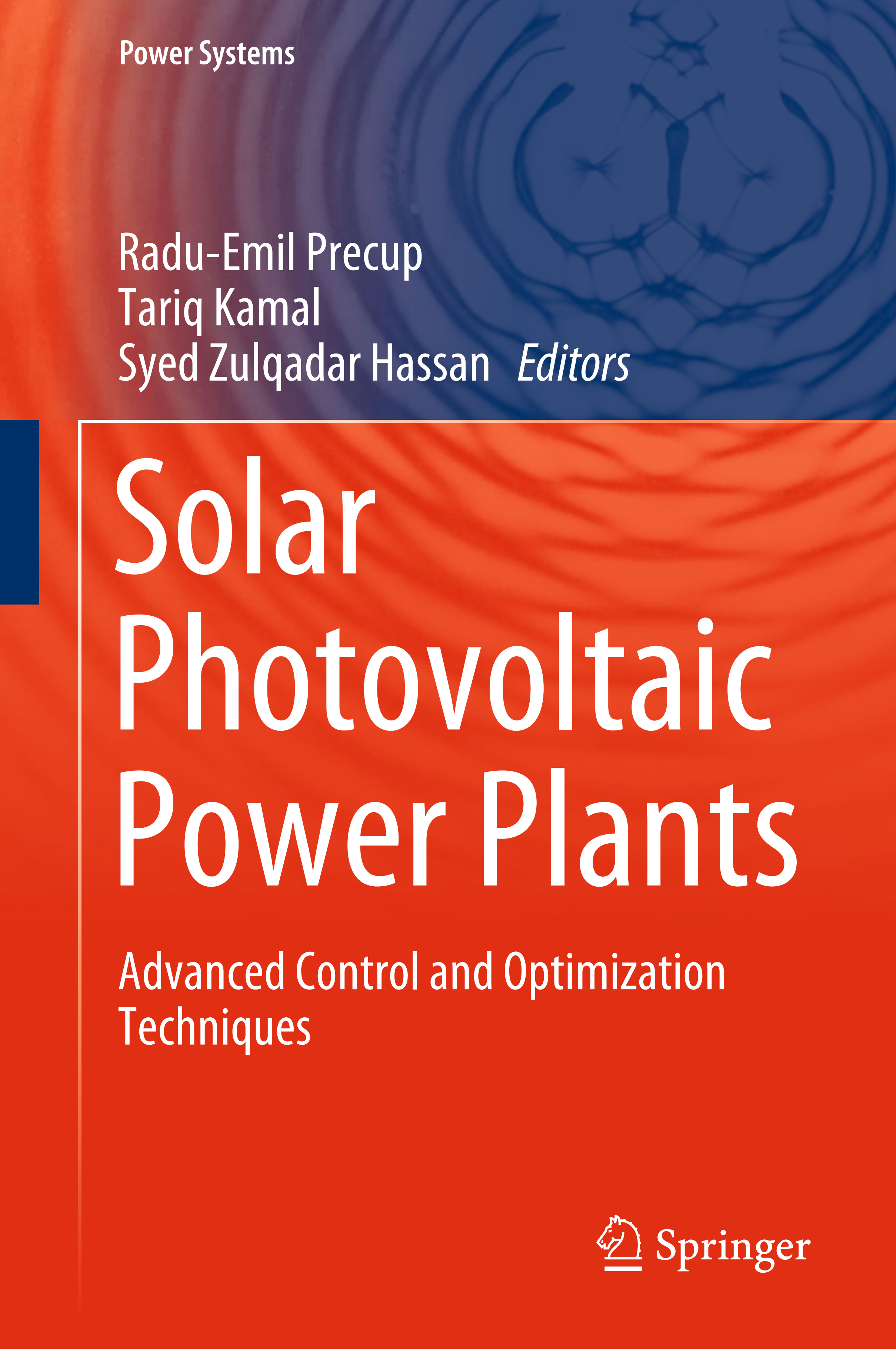

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Solar Photovoltaic Power Plants

Advanced Control and Optimization Techniques

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Preface

Growing adversarial environmental impact, escalating energy demand, ever-expanding utilization of fossil fuels coupled with rising production costs have brought substantial attention to sustainable development worldwide. In this context, global efforts have been made to promote utilizing more renewable energy resources, among which solar photovoltaic contributes is one of the most promising clean energy sources to the world energy consumption. Approximately, 90% of the global installed photovoltaic systems are integrated with grid. Megawatt photovoltaic power plants are generally preferred to install in remote areas due to the requirement of wide land area. Usually, a medium voltage network is adopted to transfer power to load centers. Therefore, compact, reliable, dynamic control and system stability, photovoltaic power plant planning and optimal sitting and utilization have become increasingly important. This book discusses control and optimization techniques (i.e., improved fuzzy control, artificial intelligence, back-propagation neural network, adaptive neuro-fuzzy control, sliding-mode control, predictive control, backstepping, secant incremental gradient based on Newton–Raphson, cuckoo search algorithm, particle swarm optimization, and gray wolf optimizer) in the broadest sense, covering new theoretical results and the applications of newly developed methods in photovoltaic systems. Going beyond classical control techniques, it promotes the use of control and optimization strategies with improved efficiency, based on linearized models and purely continuous (or discrete) models and proved by appropriate performance indices. These new strategies not only enhance the performance of the photovoltaic systems, but also decrease the cost per kilowatt-hour generated.

The material of the book is organized into the following eleven chapters. All the chapters have been included in this book after a rigorous review process. Special importance was given to chapters offering novel control and optimization techniques in solar photovoltaic systems. The contributed chapters provide new ideas and approaches, clearly indicating the advances made in control system analysis and simulation with respect to the existing state-of-the-art.

Inverter (DC–AC converter) is the key interface between the solar photovoltaic array and mains in the grid-integrated photovoltaic system. The inverter must follow the frequency and voltage of the grid and extract maximum power from the solar photovoltaic. Therefore, the quality of the output current in an inverter integrated photovoltaic systems is an important standard. Chapter "Adaptive Control Techniques for Three-Phase Grid-Connected Photovoltaic Inverters" provides the development of model reference adaptive control techniques for grid-connected photovoltaic inverter systems under uncertain parameters and disturbances. The control objectives are analyzed based on the photovoltaic inverter output requirement. The ability to compensate grid-side harmonic disturbances and asymptotic adaptive disturbance rejection is enhanced.

The output power of a photovoltaic system depends on solar radiation that falls on its PN junction as well as the percentage of solar radiation it converts into electricity (conversion efficiency). Since there is always a unique maximum power point on each power–voltage curve, maximum power point tracking units should be utilized in photovoltaic sources to increase their efficiency. Chapter "Application of Sliding-Mode Control for Maximum Power Point Tracking of PV Systems" presents one-loop and two-loop sliding-mode control schemes to increase the efficiency in photovoltaic systems. A maximum power point searching unit is utilized in the searching loop, and a tracking controller is utilized in the other loop to extract the maximum photovoltaic power photovoltaic power source.

In photovoltaic systems, DC bus voltage balancing is critical. Fluctuations in bus voltage cause power imbalance that originates from different sources of disturbances such as sudden change in load and/or weather parameters. Such a power imbalance results in extra energy. Chapter "Predictive Control of Four-Leg Converters for Photovoltaic Energy Systems" is devoted to predictive control of four-leg converters for photovoltaic systems. The predictive current control enables grid-connected operation, whereas predictive voltage control is used for stand-alone operation of photovoltaic energy systems. The predictive control strategies fulfill the control requirements concerning output current control, load voltage control, balancing of DC link capacitor voltage, and neutral-leg switching frequency minimization. Chapter "A Novel Maximum Power Point Tracking Method for Photovoltaic Application Using Secant Incremental Gradient Based on Newton Raphson" discusses some common algorithms dedicated to maximum power point tracking of the photovoltaic system such as perturb and observe, particle swarm optimization and gray wolf optimizer. The chapter also develops a new maximum power point tracking method for photovoltaic application using secant incremental gradient based on Newton–Raphson method. The proposed method has better performance in achieving global maximum power point with more tracking efficiency and convergence speed versus classical methods.

Solar photovoltaic experiences some deficiencies and some fundamental problems when utilized as a stand-alone energy source. In this context, solar photovoltaic is integrated with certain power sources and/or storage systems in a hybrid power system to increase the reliability. Chapter "Study on Control of Hybrid Photovoltaic-Wind Power System Using Xilinx System Generator" describes a photovoltaic–wind hybrid power system using a Xilinx system generator. Maximum power point tracking techniques are adopted in order to extract the maximum energy from the renewable energy sources. The virtual flux-oriented control scheme is adopted to control the grid-connected three-phase inverter based on the backstepping approach.

Over the last few years, fuzzy, neural networks, and other artificial intelligence techniques have contributed substantially in the modeling, control, and optimization of solar photovoltaic systems. Chapter "Artificial Intelligence for Photovoltaic Systems" presents an overview on the applications of artificial intelligence techniques in photovoltaic systems. Particular attention is devoted to forecasting and modeling of meteorological data, basic modeling of solar cells, and sizing of photovoltaic systems. A comparison between conventional techniques and the added benefits of using machine learning methods is given. Similarly, Chapter "Applications of Improved Versions of Fuzzy Logic Based Maximum Power Point Tracking for Controlling Photovoltaic Systems" reviews the applications of different conventional and improved fuzzy logic-based maximum power point tracking techniques in photovoltaic systems. Based on simulation and experimental results, the chapter provides a comparative study considering the main assessment criteria such as fast convergence, conversion efficiency, algorithm's complexity, and practical implementation to figure out the relative merits and limitations of the available maximum power point tracking techniques.

Chapter "A New Method for Generating Short-Term Power Forecasting Based on Artificial Neural Networks and Optimization Methods for Solar Photovoltaic Power Plants" introduces the application of artificial neural networks and particle swarm optimization to generate short-term power forecasting for solar photovoltaic plants. Power prediction is estimated using real-time data of 1 MW photovoltaic power plant in use. Estimation power data are compared with real-time data, and the precision of the proposed method is demonstrated. Chapter "Evaluation on Training Algorithms of Back Propagation Neural Network for a Solar Photovoltaic Based DSTATCOM System" suggests a back-propagation neural network control algorithm based on fast Fourier transform control algorithm for distribution static compensator integrated solar photovoltaic systems. Harmonic elimination in terms of accuracy, number of iterations (epochs), and training time has been improved in the proposed algorithm.

Chapter "Power Extraction from PV Module Using Hybrid ANFIS Controller" presents the implementation of a hybrid adaptive neuro-fuzzy inference system controller for maximum power extraction from PV module. This chapter also provides the effect of load impedance and converter topologies on adaptive neuro-fuzzy inference system controller design. The hardware results are very promising and show that the adaptive neuro-fuzzy inference system control system performance is better than other conventional control systems in terms of efficiency, stability, and precision. Chapter "An Online Self Recurrent Direct Adaptive Neuro-Fuzzy Wavelet Based Control of Photovoltaic Systems" focuses on a new wavelet-based online direct adaptive neuro-fuzzy control of photovoltaic systems. The conversion efficiency and output power are better than the well-known used traditional and intelligent maximum power point tracking controllers.

Timişoara, Romania
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Adaptive Control Techniques for Three-Phase Grid-Connected Photovoltaic Inverters

Wanshi Hong, Gang Tao and Hong Wang

Abstract This chapter presents a framework of model reference adaptive control (MRAC) techniques for three-phase grid-connected photovoltaic (PV) inverter systems with uncertain parameters and disturbances. Such adaptive controllers are employed to achieve two main goals: (i) the asymptotic tracking for the output of a time-varying reference signal by the PV system with high-order dynamics and parameter uncertainties, which cannot be achieved by some conventional control techniques, and (ii) the asymptotic rejection of a practical class of unknown high-order harmonic signal disturbances, which is crucial for desired PV system operations. In this chapter, a full PV inverter system dynamic model is derived, and adaptive control design conditions are verified for such system models. An MRAC based disturbance rejection scheme is also developed for the PV inverter system with parameter and disturbance uncertainties. Desired system performances are ensured analytically and simulation results are listed to verify the result. This study shows the potential advantages of using adaptive control techniques for PV inverter systems, for ensuring desired PV system stability, output tracking, and disturbance rejection properties.

Nomenclature

$\delta(t)$	System disturbance term
ω	Grid fundamental frequency
$\omega(t)$	Compact form of signals
$\Psi(t)$	Estimate of high frequency gain matrix
ρ_i	Control relative degrees of ith control input
$\Theta(t)$	Parameter estimates

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Θ^*	Compact form of nominal parameters
$\tilde{\Theta}(t)$	Difference between parameter and its estimates
$\varepsilon(t)$	Estimation error
$\xi(t), \zeta(t)$	Estimation signals
$\xi_m(s)$	Left interactor matrix
A, B, B_d, C	Inverter system parameters
a_{ij}^*	jth coefficient of $d_i(s)$
C_f	Filter capacitance
$d_i(s)$	Polynomial at ith diagonal term at the left interactor matrix
$d_{a,b,c}$	Three phase duty cycle
$e(t)$	Tracking error
$G(s)$	Transfer matrix of inverter system
$i_{g,a,b,c}$	Grid side three-phase current
I_{gd}, I_{gq}	Inverter d-q axis output current
I_{gd}^*, I_{gq}^*	Reference d-q axis current signals
$i_{i,a,b,c}$	Inverter side three-phase current
I_{PV}, U_{PV}	Input current and voltage of the inverter system
$K_1(t), K_2(t), K_{3f}(t)$	Adaptive control parameter estimate
K_1^*, K_2^*, K_{3f}^*	Nominal control parameter
K_p	High frequency gain matrix
L_6	Observability matrix of inverter system
L_f	Inverter side filter inductance
L_g	Grid side filter inductance
$m(t)$	Normalize matrix
P	Active power
P^*	Maximum power point
Q	Reactive power
$r(t)$	Reference input
R_f, R_g, R_c	Filter ESR
S_6	Controllability matrix of inverter system
S_p, Γ_p, K_s	Gain matrices
T	DQZ transformation
t	Time variable
$U_{a,b,cN}$	Grid voltage in a-b-c axis
u_{abc}	Control signal in a-b-c axis
$U_{c,a,b,c}$	Three-phase capacitance voltage
$U_{d,qN}$	Grid voltage in d-q axis
$U_{d1N}, U_{d,q6s,cN}$	Grid side voltage magnitudes
$W_m(s)$	Reference model
x	State representation
$x_{a,b,c}$	State representation in a-b-c reference frame
$x_{d,q,o}$	State representation in d-q-o reference frame
$y(t)$	Inverter output signal
$y_m(t)$	Reference output signal.

1 Introduction

This section introduces the photovoltaic (PV) inverter and provides background about renewable energy and some conventional control methods for PV inverter systems. It then describes the state-of-the-art research into the PV inverter control problem.

1.1 Research Motivation

Solar energy is inexhaustible and eternal. Most energy on Earth comes directly or indirectly from the sun. Every year, about 1.8×10^{18} kWh of energy is radiated from the sun to Earth, that is about 10 thousand times more than Earth's power consumption. The use of photovoltaic (PV) energy has become a trend around the world. By the end of 2015, the USA ranked the fourth for solar energy usage in the world. By the end of 2016, USA had 40 GW of installed PV capacity, which is almost twice as much as the PV capacity for the previous year [1]. From February 2016 to January 2017, utility-scale solar power generated 35.5 TWh, or 0.92% of total U.S. electricity demand. All these figures show the important strategic position of solar energy in the field of power generation.

PV Inverter

A PV inverter is a crucial part of the power system because it converts the direct current (DC) of the PV power generation devices (such as solar panels) into an acceptable utility frequency alternating current (AC) for grid-connected or off-grid users [2]. Hence, PV inverters are the core of any PV power generation system (grid-connected or off-grid). The quality of the output current of a PV inverter is an important inverter standard, so the control strategy for inverter systems has been studied to guarantee the desired output quality [3, 4]. Moreover, to have a PV inverter work most efficiently, the output current of the inverter should follow the reference currents that are obtained from the Maximum Power Point Tracking (MPPT) module (to be introduced in Sect. 2).

Major Technical Problems for PV Inverter Systems

With the continuously increasing demand for solar energy over the past decades, the grid-connected PV inverter system control problem has been of a great research interest. However, the large variations in weather mean sunlight intensity is often uncertain and the distributed installation of solar panels makes it difficult to detect system damages. These factors will lead to difficulties in controlling the PV inverters to assure that they work efficiently. As a result, improving the reliability of PV inverter systems has been a major research task. The main technical problems are as follows:

- *Randomness of the energy source.* For a renewable power source, random effects such as temperature, environment, or light intensity can influence the inverter system output. Therefore, the controller for the inverter should have the ability to make the inverter output track a given time-varying reference signal, which is obtained from the MPPT module.

- *Harmonic pollution.* For inverter systems, the power of electronic devices might cause the output current harmonics to increase. Moreover, when a polluted grid is connected to a PV inverter system, i.e., the grid-side current contains harmonic components, this will influence the performance of the PV inverter system. Thus, the PV inverter system should have the ability to reduce high-order harmonic influences.
- *Islanding effect.* An islanding effect occurs when the grid is powered off but the PV system does not detect this and continues working alone. This condition endangers power company customers and workers. Other protections, such as the isolation of AC and DC units, should also be applied to prevent the inverter from causing damage to the grid. Thus, PV systems should have anti-islanding protection modules [5].
- *Parameter uncertainty.* System uncertainties have major influences on PV inverter systems due to the unreliable characteristics of the solar energy source. A major challenge in grid integration for distributed PV systems is the unknown system uncertainties. Adaptive control technology has the desired potential to solve these problems.

Conventional Control Methods and Their Drawbacks

A Proportional and Integral (PI) controller [6, 7] and a PI controller combined with a Proportional and Resonant (PI + PR) controller are most commonly used by the photovoltaic industry. However, some weak points still remain in these conventional controllers: (i) The classical PI controller does not have the ability to deal with harmonic effects from the grid. (ii) Although a PI + PR controller can reduce the effect of the harmonics, for three-phase inverter systems the controller structure is rather complicated [3]. They may not work for distributed PV systems whose orders are high. (iii) Tracking of a time-varying reference signal cannot be achieved only by using classical controllers, which is a major issue for PV systems because the reference signal is generated from the online updating MPPT module. This drawback will cause some major problems in achieving integrated control of distributed PV inverter systems, which require control cooperation. (iv) The PV system uncertainties cannot be effectively handled by conventional methods.

System Uncertainty Issue

System uncertainties have major influences on a PV inverter system because of the unreliable characteristics of the renewable energy source. That is, (i) the uncertainty of system parameters, such as inverter system resistance or inductance; (ii) the uncertainty of the output voltage of the photovoltaic generation devices, such as solar panels; and (iii) the uncertainty of system loads and faults (for distributed PV inverter systems, the distance among the solar panels can lead to different sunlight intensity for each inverter system, and there are uncertain factors such as load variation and failure or damage of system components). A major challenge in grid integration for distributed PV systems is the system uncertainty problem, but the adaptive control technique has the desired potential to solve the main uncertainty issues.

Hence, advanced adaptive control techniques that can effectively deal with system uncertainties are needed to improve PV inverter system reliability.

Adaptive Control

In this chapter, the ability of adaptive control techniques to meet the desired control objectives of PV inverter systems is studied. Adaptive control is particularly aimed at the design of controllers for the system that has uncertainties [8] (including environmental, structural, and parameter uncertainties). These sources of uncertainty are common to power systems. Payload variation or component aging cause parametric uncertainties. In power systems, PV and other types of renewable energy-based power systems, in particular the randomness of input power sources such as solar energy and wind power also leads to parametric uncertainties. Component failure in a power system leads to structural uncertainties, and external weather influences and harmonic effects are typical environmental uncertainties. Adaptive control has been successful in addressing new challenging problems and offering encouraging solutions, when dealing with uncertainties that often appear in automobile engines, electronic devices, and other industrial processes.

Unlike other control methods like proportional-integral-derivative (PID) control [9], robust, optimal, or nonlinear control [10] methods, which require a certain knowledge of system parameters, adaptive controllers do not require such knowledge and they use online performance error information to adapt parameter uncertainties [11, 12].

1.2 Literature Review

Many research approaches have been taken to improve the reliability of PV inverter systems. In this chapter, we introduce some exciting methods that address the improvement of the control strategy of PV inverter systems.

In [3], the authors developed PI + PR control techniques for PV inverter systems to eliminate the high-order harmonic effects. The function of a PR controller is to eliminate the harmonics in a particular frequency, in which frequency the harmonic component cannot be reduced by the PI controller. In this research, a specific method of modeling the inverter has been applied. In [4], the authors constructed classical controllers for the inverter using LCL filters. This method eliminated the current harmonics and the basic control objectives of an inverter system. However, for the three-phase inverter, the topology of the control structure is rather complicated because of the complexity of the three-phase system, and the uncertainty problem for the PV inverter systems has not been considered.

In [13], the authors used an LCL filter in the inverter system to physically eliminate high-order harmonics, derived an inverter system model with an LCL filter, and developed a controller for this type of inverter system. In this chapter, the significance of the LCL filter is mentioned, because an LCL filter can improve the efficiency of filtering and also reduce the volume of the filter. The authors used a classical control method for the inverter control problem, and they did not consider the harmonic problem for this system. Moreover, with this improvement for the PV inverter systems, the controller will be harder to design because the order of the filter system has increased.

In [14], three-phase inverter control using a nonlinear Kalman filter is introduced. This paper develops a nonlinear approach to the inverter system using a Kalman filter. To simplify the control problem, in this research the authors proposed to directly control the power to track the maximum power point P^*.

In [15–17], some adaptive approaches to the PV inverter control problem are given. In [17], an adaptive control scheme was used to help predict the system parameters when the system is working in a polluted environment. However, the authors still used the classical PI + PR controller for control of the main circuit. In [15], an adaptive droop control was also used to help predict system parameters. A simple adaptive control design was developed in [16] by only considering the off-grid case without an LCL filter in the inverter system.

1.3 Technical Contributions

From the discussion above, it can be seen that it is crucial to develop a reliable controller to deal with high-order harmonics disturbances and system uncertainties, so as to achieve the output tracking of a time-varying signal for PV inverter systems. This need motivated our research on multivariable model reference adaptive control (MRAC) techniques for PV inverter systems. The main contributions of this work are the following:

- The control objectives are analyzed based on the PV inverter output requirement.
- The ability to compensate grid-side harmonic disturbances and asymptotic adaptive disturbance rejection is enhanced.
- A state feedback output tracking MRAC scheme is developed with some key techniques established for PV inverter systems.

The remainder of this chapter is organized as follows. Section 2 first introduces the details of three-phase grid-connected PV inverter systems, then derives a model for three-phase PV inverter systems, and analyzes control objectives for three-phase PV inverter systems. Section 3 develops an adaptive control design for the PV inverter system and analyzes the stability of the inverter system relative to the proposed adaptive control design. Section 4 presents a simulation study using the developed adaptive controller to verify the desired system performance. Section 5 summarizes this chapter and discusses the future topics related to this research.

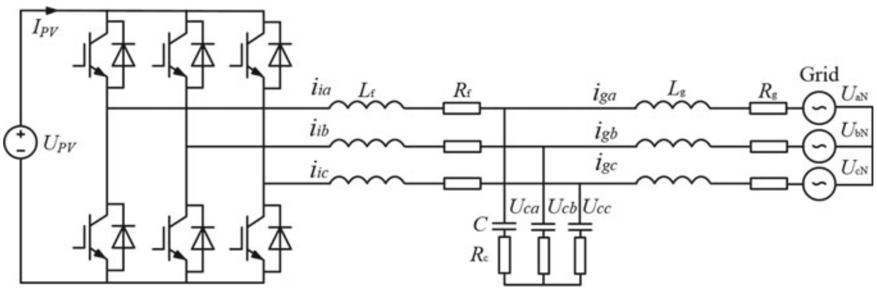

Fig. 1 Inverter circuit structure [18]

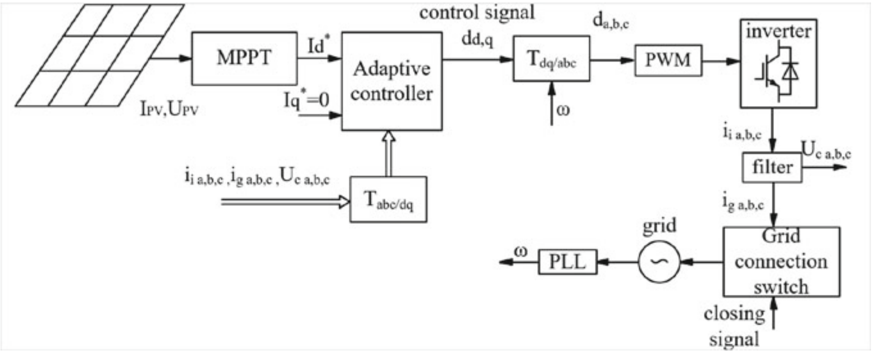

Fig. 2 Adaptive PV inverter control system structure [18]

2 PV Inverter System Modeling

The function of a three-phase inverter is to manipulate the input DC voltage and current with switching signals to change it into the desired three-phase AC current. Figure 1 shows the circuit structure of the three-phase grid-connected PV inverter system. The solar panel generates current and voltage (I_{PV} and U_{PV}), which are the input of this inverter system. The current and voltage go through a series of insulated gate bipolar transistors (IGBTs) and are converted to inverter side current $i_{i,a,b,c}$. Passing the LCL filter (represented by L_f, L_g and C_f, R_f, R_g, and R_c, which are the Equivalent Series Resistance) the inverter-side current is filtered and the inverter system produces the output $i_{g,a,b,c}$.

The adaptive control system structure is shown in Fig. 2, where the subscripts a, b, c in the signals $d_{a,b,c}$, $i_{i,a,b,c}$, $U_{c,a,b,c}$ etc., denote three components of each signal. Our adaptive controller controls the switching state of the IGBTs to have the PV inverter system constantly operating at the maximum power point P^*. To achieve this goal, our adaptive controller should correspond with each module in the inverter system. The reference current signals I_{gd}^*, I_{gq}^* are for the inverter output current I_{gd}, I_{gq} to track. In this design, we assume that $I_{gq}^* = 0$ for all time for simplicity, which means that the reference output power contains no reactive power. For applications, the reactive power can be set to nonzero elements. In such cases, I_{gq}^* can be time-varying as well. The control strategy to track $I_{gq}^*(t)$ is similar to the tracking of I_{gd}^* introduced in this chapter. The control signal u_{abc} represents the duty cycles of the pulse-width modulation (PWM) waveform [19], which generates switching signals to the IGBTs inside the inverter and produces the inverter-side currents $i_{i,a,b,c}$. In this process, the DC-side current is changed to the desired AC output current. Passing through the LCL filter, the final outputs $i_{g,a,b,c}$ are obtained. Before the grid connection, an outer control loop is required to confirm whether the phase and magnitude of the inverter output voltage are identical to the grid side voltage. Thus, a closing signal generation module is required. Our work was to design the adaptive controller (shown in Fig. 2) to track the maximum power point and cooperate with other system components shown in Fig. 2.

Maximum Power Point Tracking

The MPPT module is a crucial part of the inverter system. For different solar panels that have different insolation, there is a maximum power point within the allowed range of the voltage (i.e., dependent on the variation of the sunlight intensity). The goal of MPPT is to find the maximum power point P^* which is used in the latter part of the system to calculate the reference current for the adaptive controller. This process constantly updates the maximum power point P^*.

LCL Filter

The conventional three-phase grid-connected inverter uses an LC filter or just an L filter. However, with the power level of the inverter advanced to a new level, the power electronic devices require a lower switching frequency to eliminate the power loss, which will lead to an increase in the high-order harmonics of the grid side. As a result, to meet the total harmonic distortion (THD) standard, the inductance will become very high if one only uses the L filter. This will lead to a series of problems that will cause not only higher cost and and require a larger size for the system, but also increase the inductance affecting the system dynamically. Recently, the replacement of the L filter by an LCL filter has been one of the most modern solutions for solving the above problems. LCL filters show better performance in reducing the high-order harmonics with a lower total inductance.

Grid-Connecting Process

As one of the crucial technical aspects of the inverter control problem, the inverter system first should generate voltage that has some related magnitude, the same phase, and the same frequency as the grid side. The grid-connecting process follows two steps:

Step 1 The inverter should first start working in isolation from the grid using a transformer to generate three-phase voltage that has the same magnitude as the grid side voltage. The maximum tolerance error for the output voltage is 10% of the rated voltage [20].

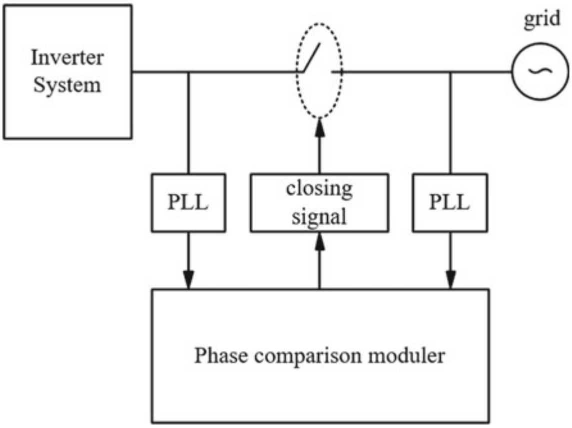

Fig. 3 Scheme diagram for the inverter-grid connecting process

Step 2 With the inverter generating the same magnitude of the three-phase voltage, the phase tracking method is used to generate the closing signal [21, 22]. The basic principle is to connect the inverter to the grid at the moment when the inverter system output has the same frequency and the same phase as the grid.

With the above steps accomplished, the inverter system can be successfully connected to the grid. A block diagram showing the control of the grid-connection process is provided in Fig. 3. In this chapter, we are mainly considering the current control problem for the grid-connected system, which occurs after this grid connection process is accomplished.

Inverter System Modeling

We can write the three-phase circuit dynamic equations from Fig. 1 as follows:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} I_{ia} \\ I_{ib} \\ I_{ic} \end{bmatrix} = \frac{u_{PV}}{\sqrt{3}L_f}\begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} - \frac{R_f}{L_f}\begin{bmatrix} I_{ia} \\ I_{ib} \\ I_{ic} \end{bmatrix} - \frac{R_c}{L_f}\begin{bmatrix} I_{ia}-I_{ga} \\ I_{ib}-I_{gb} \\ I_{ic}-I_{gc} \end{bmatrix} - \frac{1}{L_f}\begin{bmatrix} U_{ac} \\ U_{bc} \\ U_{cc} \end{bmatrix} \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} I_{ga} \\ I_{gb} \\ I_{gc} \end{bmatrix} = \frac{1}{L_g}\begin{bmatrix} U_{ac} \\ U_{bc} \\ U_{cc} \end{bmatrix} + \frac{R_g}{L_g}\begin{bmatrix} I_{ia} \\ I_{ib} \\ I_{ic} \end{bmatrix} + \frac{R_c}{L_g}\begin{bmatrix} I_{ia}-I_{ga} \\ I_{ib}-I_{gb} \\ I_{ic}-I_{gc} \end{bmatrix} - \frac{1}{L_g}\begin{bmatrix} U_{aN} \\ U_{bN} \\ U_{cN} \end{bmatrix} \tag{2}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} U_{ac} \\ U_{bc} \\ U_{cc} \end{bmatrix} = -\frac{1}{C_f}\begin{bmatrix} I_{ia}-I_{ga} \\ I_{ib}-I_{gb} \\ I_{ic}-I_{gc} \end{bmatrix}, \tag{3}$$

where $[d_a, d_b, d_c]^T = u(t)$ is the control vector, which are the duty cycles of the PWM module.

To achieve maximum power point tracking, we need to change (1)–(3) into d-q-0 axis by applying the following *DQZ* transformation T [23–25]

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ -\sin(\omega t) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right), \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}, \tag{4}$$

$$\begin{bmatrix} x_d \\ x_q \\ x_o \end{bmatrix} = T \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \Leftrightarrow \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = T^{-1} \begin{bmatrix} x_d \\ x_q \\ x_o \end{bmatrix} = T^T \begin{bmatrix} x_d \\ x_q \\ x_o \end{bmatrix}, \tag{5}$$

where $TT^T = I$. Because no neutral line connection existed, based on the properties of this three-phase circuit topology, all terms related to 0 will be zero [23].

Thus, the state-space model for d-q-0 axis will contain six states. This process also reduces the number of unknown parameters to be estimated. Note that an accurate phase tracking is for this coordinate transformation process. More studies about phase tracking can be found in [21, 22].

State-Space Equation

The state-space model in d-q-0 axis is

$$\dot{x}(t) = Ax(t) + Bu(t) + B_d\delta(t),\ y(t) = Cx(t), \tag{6}$$

where

$$x = \left[I_{id}\ I_{iq}\ I_{gd}\ I_{gq}\ U_{dc}\ U_{qc}\right]^T,\ u = \left[d_d\ d_q\right]^T, \tag{7}$$

$$A = \begin{bmatrix} -\frac{R_f+R_c}{L_f} & \omega & \frac{R_c}{L_f} & 0 & -\frac{1}{L_f} & 0 \\ -\omega & -\frac{R_f+R_c}{L_f} & 0 & \frac{R_c}{L_f} & 0 & -\frac{1}{L_f} \\ \frac{R_c+R_g}{L_g} & 0 & -\frac{R_c}{L_g} & \omega & \frac{1}{L_g} & 0 \\ 0 & \frac{R_c+R_g}{L_g} & -\omega & -\frac{R_c}{L_g} & 0 & \frac{1}{L_g} \\ \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix}, \tag{8}$$

$$B = \begin{bmatrix} \frac{U_{PV}}{\sqrt{3}L_f} & 0 & 0\,0\,0\,0 \\ 0 & \frac{U_{PV}}{\sqrt{3}L_f} & 0\,0\,0\,0 \end{bmatrix}^T,\ B_d = \begin{bmatrix} 0\ 0 & -\frac{1}{L_g} & 0 & 0\ 0 \\ 0\ 0 & 0 & -\frac{1}{L_g} & 0\ 0 \end{bmatrix}^T, \tag{9}$$

$$C = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 0\ 0\ 1\ 0\ 0\ 0 \\ 0\ 0\ 0\ 1\ 0\ 0 \end{bmatrix},\ \delta = \left[U_{dN}\ U_{qN}\right]^T, \tag{10}$$

where $u(t) = [d_d, d_q]^T$ is the control vector, and δ is the grid side voltage. A, B, B_d and C are the parameter matrices that contain all the system parameters. This state-space model is the plant to construct adaptive control design.

Inverter Requirements

To obtain the control objectives, we need to analyze the requirements for the inverter output: