MODELING AND CONTROL OF GRID CONNECTED PHOTOVOLTAIC SYSTEM: A REVIEW

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ABSTRACT

The sale of electric energy generated by photovoltaic plants has attracted much attention in recent years. The installation of PV plants aims to obtain the maximum benefit of captured solar energy. The different techniques of modeling and control of grid connected photovoltaic system with objective to help intensive penetration of photovoltaic (PV) production into the grid have been proposed so far in different papers. The current methodologies for planning the design of the different components of a PV plant are not completely efficient. Therefore lot of research work is required for overall configuration of the grid connected PV system, the MPP tracking algorithm, the synchronization of the inverter and the connection to the grid. This paper focuses on the solar energy, grid connected photovoltaic system, modeling of photovoltaic array, maximum power point tracking, and grid connected inverter. This paper helps the researchers to know about the different methods presented so far for modeling and control of grid connected photovoltaic system so that further work on integration of solar energy with grid can be carried out for better results.

KEYWORDS: Grid-Connected Inverter, Grid-Connected PV System, Maximum Power Point Tracking, Performance Conditioning System, Photo-Voltaic Array

INTRODUCTION

The conventional energy sources, obtained from our environment, tend to exhaust with relative rapidity due to its irrational utilization by the humanity. Renewable energy offers a promising alternative source. Solar energy seems to be most attractive nowadays. The quantity of energy from the sun that arrives on the earth surface in a day is ten times more than the total energy consumed by all people of our planet during a year [1]. Photovoltaic (PV) energy has great potential to supply energy with minimum impact on the environment, since it is clean and pollution free [2]. The grid integration of Renewable Energy Sources (RES) applications based on photovoltaic systems is becoming today the most important applications of PV systems, gaining interest over traditional stand-alone systems [3]. Four different system configurations are widely developed in grid-connected PV power applications: the centralized inverter system, the string inverter system, the multi string inverter system and the module-integrated inverter system [4]-[5].

In the grid-connected PV system, power electronic inverters are needed to realize the power conversion, grid interconnection, and control optimization [6]-[7]. Generally, grid-connected pulse width modulation (PWM) voltage source inverters (VSI) are widely applied in PV systems. For the inverter based PV system, the conversion power quality including the low THD, high power factor, and fast dynamic response, largely depends on the control strategy adopted by the grid-connected inverters. The strict regulations have been applied to the equipment connected to the utility lines to maintain the grid security. Some of these regulations relate to harmonic distortion and power factor. The growing use of power electronics has tendency of the harmonic distortion levels to increase. Therefore the increasing integration of photovoltaic energy with electric transmission and distribution network has been a challenge for planners and researchers.
This paper presents a review of modeling and control of grid connected photovoltaic system proposed by the researchers recently.

This paper is organized as follows: Section II presents solar energy and Indian renewable energy at a glance. Different components and literature survey of grid connected photovoltaic system is presented in section III. Photovoltaic array modeling and maximum power point tracking with literature survey are presented in section IV and V respectively. Finally in section VI, the literature survey of grid connected inverter is presented.

**SOLAR ENERGY**

For solar power, there is the natural diurnal cycle of variability in insolation [incident solar radiation]. The position of the sun influences the incidence of the solar rays on the solar cells, resulting in a noticeable variation of the power output. Also hours of sun vary with the time of the year. The solar power decreases in the autumn and winter and is higher in spring and summer [8]. Solar energy is abundant and offers a solution to fossil fuel emissions and global climate change. Earth receives solar energy at the rate of approximately 1, 20,000 terawatt (1 TW = 1012 watt or 1 trillion watt). This enormously exceeds both the current annual global energy consumption rate of about 15 TW, and any conceivable requirement in future [9]. The cloud cover can cause significant ramps in solar insolation and electric power output. Solar insolation can change by more than 80% of the peak insolation in a matter of seconds [10]. The corresponding ramp in the solar power plant output is also very large but it also depends on panel size and geographical spread. In addition, inverter tripping adds to the variability in solar plant output. The generation characteristics of renewable energy sources are variable in nature. At present the electric power system operations are designed to accommodate the natural (and very large) variability in load demand as well as planned and unplanned contingencies. It has been suggested that existing mechanisms to handle demand fluctuations are adequate for renewable generation variability up to 20% penetration levels [11]. Advanced control strategies are required to integrate renewable energy sources more than 20% penetration level.

India is one of the fastest growing countries in terms of energy generation and consumption. Currently, it is the fifth largest consumer of energy in the world, and will be the third largest by 2030 [12]. India’s current RE base is 22233 MW and it is 11.66% of total installed capacity of 190.59 GW (Feb. 2012). India stands 4th in the installed power generation capacity using RE sources. The Green peace International, European Renewable Energy (EREC) reports (March, 2009) has projected that by 2050, about 69% of the electricity produced in India will come from RE sources. ‘New’ renewables – mainly wind, solar thermal energy and PV will contribute almost 40%. The Country has an estimated RE potential of around 88,081 MW from available exploitable sources as given in Table I [13].

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<tr>
<td><strong>A. Grid Connected</strong></td>
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<tr>
<td>Wind</td>
<td>48500</td>
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<td>Cogeneration-bagasse</td>
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<tr>
<td>Waste to Energy</td>
<td>2700</td>
<td>73.46</td>
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<tr>
<td>Solar PV and Thermal</td>
<td>50 MW/Sq. km</td>
<td>481.48</td>
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<td>Total A</td>
<td>88081</td>
<td>23129.40</td>
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<td><strong>B. Off-Grid</strong></td>
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<tr>
<td>Waste to energy</td>
<td>92.93</td>
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<tr>
<td>Biomass (non-bagasse co-generation)</td>
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<td>Biomass gasifier</td>
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GRID CONNECTED PHOTOVOLTAIC SYSTEM

The photovoltaic (PV) power generation systems are renewable energy sources that expected to play a promising role in fulfilling the future electricity requirements [14]-[16]. The PV systems principally classified into stand-alone, grid-connected or hybrid systems. The grid-connected PV systems generally shape the grid current to follow a predetermined sinusoidal reference using hysteresis-band current controller, which has the advantages of inherent peak current limiting and fast dynamic performance [17]-[18]. Fig.1 shows the schematic diagram of a grid connected PV system [19]-[20]. It typically consists of two main parts: the PV array and the power conditioning unit (PCU). The PCU typically includes:

- A Maximum Power Tracking (MPPT) circuit, which allows the maximum output power of the PV array.
- A Power Factor (PF) control unit, which tracks the phase of the utility voltage and provides to the inverter a current reference synchronized with the utility voltage.
- A converter, which can consist of a DC/DC converter to increase the voltage, a DC/AC inverter stage, an isolation transformer to ensure that the DC is not injected into the network, an output filter to restrict the harmonic currents into the network.

![Figure 1: Schematic Diagram of Grid-Connected PV System](image)

The model of grid connected photovoltaic system to control active and reactive power injected in the grid is presented in [21]-[22]. Pires et al. [23] presented a grid connected photovoltaic system with a multilevel inverter and a Le-Blanc transformer. The proposed multilevel power converter uses two single-phase voltage source inverters and a four wire voltage source inverter. The Le-Blanc transformer is connected at the output of the multilevel inverter. The configuration of the PV system is based on the multi-string technology. The structural design of this new power converter allows a seven level shaped output voltage wave at the output of multilevel inverter. To control this power converter a sliding mode controller with a vectorial modulator is used. Makhlouf et al. [24] described the modeling and control of a single-phase grid connected photovoltaic system. The MPPT algorithm, the synchronization of the inverter and the connection to the grid are discussed. Tracking the DC voltage and current allows MPP calculation which gives the inverter to function efficiently. Makhlouf et al. [25] presented modeling of the grid-connected photovoltaic distributed generation system. The
detailed modeling of PV system components, in Simulink/ MATLAB software is presented. Yann Riffonneau et al. [26] presented an optimal power management mechanism for grid connected photovoltaic systems with storage. The objective is to help intensive penetration of PV production into the grid by proposing peak shaving service at the lowest cost. The structure of a power supervisor based on an optimal predictive power scheduling algorithm is proposed. Optimization is performed using Dynamic Programming and is compared with a simple ruled-based management. Hicham Fakham et al. [27] presented power control design of a battery charger in a hybrid active PV generator for load-following applications. A hybrid generator with a PV energy conversion system is proposed with super-capacitors and lead-acid batteries in a FC-coupled structure. The objective of this system is to supply prescribed reactive and active power to the grid. Alias Khamis et al. [28] presented the modeling and simulation of a microgrid tested using photovoltaic and battery based power generation. The microgrid using renewable energy consist of a 3kW photovoltaic, with 30 pieces of 12V for 100Ah battery bank, DC/DC converter, charge controller for battery, single phase DC/AC inverter and various loads (resistor, capacitor, inductor) are developed. The AC buses 240V voltage include with isolation transformer to simulate the grid voltage level by Matlab/Simulink software. Ahmed A.A. Hafez et al. [29] proposed a simple and efficient PI controller for single-phase grid-connected PV generator. The controller ensures the system operation at maximum power point (MPP) irrespective to atmospheric conditions. A detailed design of the controller and DC capacitor were carried out. An average value model was developed to facilitate the design of the controller and to study the system performance under different operation conditions. The results were validated by rigorous simulation.

PHOTOVOLTAIC ARRAY MODELING

Numerous PV cells are connected in series and parallel circuits on a panel for obtaining high power, which is a PV module. A PV array is defined as group of several modules electrically connected in series-parallel combinations to generate the required current and voltage. The building block of PV arrays is the solar cell, which is basically a p-n semiconductor junction that directly converts solar radiation into dc current using photovoltaic effect. The simplest equivalent circuit of a solar cell is a current source in parallel with a diode, shown in Fig. 2 [30].

![Figure 2: Circuit Diagram of a Solar Cell](image)

The series resistance $R_s$ represents the internal losses due to the current flow. Shunt resistance $R_{sh}$ in parallel with diode, this corresponds to the leakage current to the ground. The single exponential equation which models a PV cell is extracted from the physics of the PN junction and is widely agreed as echoing the behavior of the PV cell [31].

$$I = I_L - I_{sc} \left( \exp \left( \frac{V + R_s I}{I_s} \right) - 1 \right) - \frac{(V + R_s I)}{R_{sh}}$$  \hspace{1cm} (1)
Hari Prasad et al. [32] demonstrated a computer simulation derived study of photovoltaic cells/modules, utilizing MATLAB. The MATLAB is used to simulate a circuit based model for PV cells/modules and then to conduct a behavioral analysis under altering conditions of solar insolation, including blending effect, temperature, diode model variables, series and shunt resistance. J. Salazar et al. [33] used photovoltaic panel model of moderate complexity to examine the operation of a PV system with two stages connected to the AC side of the stand-alone grid. The shunt resistance $R_{sh}$ is neglected, $I_L$ is approximately equal to $I_{sc}$ and $\exp((V+R_s I)/V_t)$ is greater than 1. Rym Marouani et al. [34] presented a mathematical model of PV array used three-phase grid-connected photovoltaic system.

The number of PV modules connected in parallel and series in PV array are used in expression. The $V_t$ is also defined in terms of the ideality factor of PN junction ($n$), Boltzmann’s constant ($K_B$), temperature of photovoltaic array ($T$), and the electron charge ($q$). Guillermo et al. [35] applied a dynamical electrical array reconfiguration (EAR) strategy on the photovoltaic (PV) generator of a grid-connected PV system based on a plant-oriented configuration, in order to improve its energy production when the operating conditions of the solar panels are different. The EAR strategy is carried out by inserting a controllable switching matrix between the PV generator and the central inverter, which allows the electrical reconnection of the available PV modules.

**MAXIMUM POWER POINT TRACKING**

In order to improve the efficiency of the PV generation system, PV array should be controlled to generate the maximum power at the particular environment conditions. Maximum power point tracking (MPPT) is an essential process of self-optimization and aims at using some control algorithms to ensure the PV array to operate at the maximum power point [36]. A maximum power point tracker (MPPT) is a power electronic DC-DC converter inserted between the PV array and its load to achieve optimum matching [37].

Antoneta Iluliana Bratcu et al. [38] presented maximum power point tracking of grid-connected photovoltaic arrays by using extremum seeking control. The energy provided by array is sent to the single-phased utility grid by means of a two-stage conversion system, composed of a DC-DC boost converter and a DC-AC inverter. The performance of a control method based upon extremum seeking control (ESC) is presented, which belongs to the larger class of perturb-and-observe methods widely used for the MPPT of PV arrays. The MATLAB/Simulink numerical simulations have shown that the MPPT by ESC is quite effective at tracking strongly variable irradiance conditions.

Esram et al. [39] presented an MPPT control method based on the incremental conductance method to find the maximum power point (MPP) for all conditions, which can tell on which side of the PV characteristic the current operating point is located. Swati Bhasme et al. [40] used current feedback loop with PI controller to achieve the maximum power point of the PV array.

The measured values of PV current are compared to reference values, which correspond to the operation in the maximum point under standard climatologically conditions. Makhlouf et al. [41] presented mathematical modeling of MPPT. The voltage and current at the maximum power point are determined and hence the maximum power. K. Manohar et al. [42] used Perturb-and-observe (P&O) method to achieve maximum power point tracking and fault analysis. In literature [43]-[45], a lot of work investigating simple, efficient and minimal-knowledge-demanding methods of MPPT, like parasitic capacitance method, the incremental conductance method, the constant voltage method etc. are presented. Wenhao CAI et al. [46] used boost circuit to achieve the function of MPPT according to the advantage and disadvantages in the boost and buck circuit. Since the output voltage of PV cell is low, the uses of boost circuit will step-up the low-voltage of PV array to be allowable line voltage.
THE GRID CONNECTED INVERTER

PV array and the battery are connected to the AC grid via a common DC/AC inverter. It consists of power switching blocks. Each block of the switching blocks consists of a semiconductor switch (IGBT) and an anti-parallel diode. AC output voltage is created by switching the full bridge in an appropriate sequence [47]-[48]. The inverter topologies can be divided into two types, namely single and multi-stage inverter. The single-stage inverter has advantages such as low cost, high efficiency, robust performance, high reliability and simple structure. On the other hand, the multi-stage inverter accepts a wide range of input voltage variations, high cost, low efficiency, complicated structured and isolated topologies with high frequency transformers can extract power from the source even when DC voltage is very low [49].

Pavan Kumar et al. [50] presented a single-phase five-level photovoltaic inverter topology for grid-connected PV systems with a novel pulse width modulated (PWM) control scheme. Two reference signals identical to each other with an offset equivalent to the amplitude of the triangular carrier signal were used to generate PWM signals for the switches. The inverter offers much less THD and can operate at near unity power factor. S.J. Lee et al. [51] presented the modeling and control of the single-phase photovoltaic grid-connected five-level cascaded H-bridge multilevel inverter. For the utility power factor, the proportional and integral current controller with the duty ratio feed-forward compensation method is used. Davu Swetha et al. [52] presented control strategy of full-bridge inverter with bidirectional power flow.

Marcelo et al. [53] presented a novel high performance conditioning system (PCS) of a three-phase grid-connected PV system and its control scheme for applications in DG systems. The PCS utilizes a two-stage energy conversion system topology composed of a DC/DC boost converter and a diode-clamped three-level voltage source inverter that satisfies all the stated requirements. Ajay Krishna et al. [54] presented grid connected voltage controlled single-phase photovoltaic system with multifunctional shunt controller. S.M. Ali et al. [55] used inverter in current control method with PWM switching mechanism to make the inductance current track the sinusoidal reference current command closely and obtain a low THD injected current. In literature [56]-[61], the different aspects of grid connected inverter topologies are presented.

CONCLUSIONS

Modeling of grid connected converters for solar energy requires not only power electronics technology, but also detailed modeling of the grid synchronization and modulation techniques. Control of active and reactive power in both single and three phase grid connections can be achieved by quadrature controllers, analogous to field oriented control in electrical drives. Modulation strategies, loss determination and thermal cycling, as well as life time estimation are important factors that can be studied in detail. This article has presented a comprehensive literature review on important aspects of grid-connected photovoltaic system such as modeling of photovoltaic array, maximum power point tracking, inverter etc. It is expected that better methods of modeling and control design will make the photovoltaic system more efficient for grid integration.

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BIOGRAPHIES

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