Renewable Energy Systems With Photovoltaic Power Generators: Operation and Modeling

Jan T. Bialasiewicz, Senior Member, IEEE

Abstract—A substantial increase of photovoltaic (PV) power generators installations has taken place in recent years, due to the increasing efficiency of solar cells as well as the improvements of manufacturing technology of solar panels. These generators are both grid-connected and stand-alone applications. We present an overview of the essential research results. The paper concentrates on the operation and modeling of stand-alone power systems with PV power generators. Systems with PV array–inverter assemblies, operating in the slave-and-master modes, are discussed, and the simulation results obtained using a renewable energy power system modular simulator are presented. These results demonstrate that simulation is an essential step in the system development process and that PV power generators constitute a valuable energy source. They have the ability to balance the energy and supply good power quality. It is demonstrated that when PV array–inverters are operating in the master mode in stand-alone applications, they well perform the task of controlling the voltage and frequency of the power system. The mechanism of switching the master function between the diesel generator and the PV array–inverter assembly in a stand-alone power system is also proposed and analyzed. Finally, some experimental results on a practical system are compared to the simulation results and confirm the usefulness of the proposed approach to the development of renewable energy systems with PV power generators.

Index Terms—Autonomous power systems, master/slave inverter operation, photovoltaic (PV) systems, power system modeling and simulation.

I. INTRODUCTION

IN RECENT years, the substantial increase of research and development work in the area of photovoltaic (PV) systems have made the PV power generators a feasible alternative energy resource that complements other energy sources in hybrid energy systems. The trend of fast increase of the PV energy use is related to the increasing efficiency of solar cells as well as the improvements of manufacturing technology of solar panels. The PV generators can either be grid connected (operate in distributed generation systems) or can operate in stand-alone (autonomous) systems.

With the development of distributed generation systems, the renewable electricity from PV sources became a resource of energy in great demand. A good overview of some existing inverter topologies for interfacing PV modules to the grid is presented in [1]. The current control scheme is mainly used in PV inverter applications. Several very useful earlier studies on current PV inverters, such as [2], have been performed.

PV generation efficiency and power quality are the fundamental issues. PV power sources are usually integrated with control algorithms that have the task of ensuring maximum power point (MPP) operation. Many algorithms have been developed for tracking the maximum power point of a solar array [3]–[5]. Most commonly used are the perturb-and-observe (P&O) algorithm [3] and the incremental conductance algorithm [4]. The main disadvantages of these algorithms include oscillations around the optimal operating point and the necessity of measuring the array current. Consequently, for some time, the researchers have been focused on the improvement of maximum-power-point-tracking (MPPT) control and the reduction of total harmonic distortion (THD). The MPPT operation that increases the system efficiency will also reduce the ripple at the terminals of the PV module if the operation is performed without too much fluctuation. The reduction of current or voltage ripples is predicted as a main goal of the researchers in the years to come [6]. There are several interesting papers concerned with these issues and published in IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, vol. 53, no. 4, 2006, in a Special Section entitled “Renewable Energy and Distributed Generation Systems.” A short overview of these as well as other papers related to this topic may be beneficial to the readers and is presented below.

The real-time estimation of MPP is discussed in [7]. The work is well supported by both a comparative study in terms of accuracy of different PV modeling techniques and a set of simulation and experimental results validating the proposed approach.

As pointed out in [8], the necessity of measuring the array current can be eliminated by applying the sliding-mode observer for its estimation. The estimated current has some chattering ripples, but its average value coincides exactly with the real current average value.

A new MPPT algorithm for a small-scale dual-module integrated PV grid-connected system that consists of two PV modules is proposed in [9]. It enables a simple hardware implementation using conventional proportional–integral (PI) controllers instead of digital platforms required in other MPPT methods. Experimental results are presented.

A modified incremental conductance controller that produces a smooth transition to the MPP is discussed in [10]. It can perform the MPPT algorithm without using a dc current sensor of the PV array.

A method for MPPT control, strictly related to current weather conditions, has been developed in [11]. Effectiveness...
of the proposed method was verified through experiments under various weather conditions.

An intelligent PV module for grid-connected PV systems, presented in [12], constitutes an industrial development of existing solutions in PV module power processing and monitoring. The authors implement the design proposed by Walker and Sernia [13]. The solution reduces electrical losses and enhances system efficiency.

A prototype model of a microcontroller for grid-connected PV systems, designed to satisfy Japanese grid-connection guidelines and used for ac connection of individual solar panels, is reported in [14]. Tests confirmed the correct operation of the MPPT and islanding protection functions.

Besides the grid-connected applications of PV generators included in distributed generation systems, the increasingly important role play their stand-alone applications, in which the electric energy may also be provided by other renewable energy sources such as wind turbines and diesel generators. This paper describes the inclusion of a PV array in the simulation of such systems. It appears as a part of the PV array–inverter assembly that uses the inverter to perform dc-ac energy conversion.

Without an existing interconnected grid or a diesel generator on the system, the inverter must regulate the system’s frequency and voltage. In addition, the inverter balances the power in the system. However, to take full advantage of the wind or the solar energy resource during periods of maximum availability, a proper control system must be designed for each particular application. The design goal may be simplified to a great extent if a proper simulation tool is available. The system must maintain power quality, as measured by electrical performance. In systems with diesel generators, the PV array–inverter assembly is used as a preprogrammed power source and operates in the slave mode.

To ensure stability, power quality, and reliability, each new system should be simulated before it is implemented in the field. The simulation is intended to confirm that a particular control strategy results in the desired system performance or to reveal necessary design modifications, or both.

Using the VisSim\(^1\) visual environment, we developed a modular simulation system, called a renewable energy power system modular simulator (RPM-SIM) [15]–[17], to facilitate a low-cost application-specific study of the system dynamics of wind-solar-diesel hybrid power systems. With a library of power system and renewable energy source modules available, it is easy to set up a particular system configuration. Although some simulation studies require that the existing modules be modified or that specialized modules be included, or both, such modifications can be done rather quickly. Fig. 1 represents a single-line diagram of a stand-alone renewable-energy power system. All the elements of the simulated system are connected to one module, called the point of common coupling (PCC). Other modules included are the diesel generator (DG), the wind turbine module with the induction generator and the wind-speed time series as the input (WT), the PV array–inverter assembly, the village load (VL), and the damp load (DL).

\(^1\)VisSim is the trademark of Visual Solutions.

Fig. 1. Single-line diagram of a stand-alone renewable energy power system.

\(R + jX\) represents the transmission line renewable energy system. Power-factor-correcting capacitors.

The \(d–q\) axis convention and synchronous reference frame are used in all electrical simulations. For all modules included in the simulator, we assumed (for both real and reactive power) a general power sign convention—the power absorbed is displayed as negative, and the power generated is displayed as positive. This power convention simplifies the interpretation of the simulation results. In particular, it facilitates interpreting the instantaneous power balance.

In the following sections, we first describe the PV array–inverter assembly of the simulator. Using an example of a commercial solar panel, we explain the relationship between the I–V characteristic of a single cell and a solar panel. Next, we concentrate on the interaction of the PV array–inverter assembly with power systems. The description of this interaction, two case studies, and comparison of simulation results and recorded results of a real system illustrate the simulator’s good performance and usefulness. Finally, summarizing the paper, we discuss the potential applications of the simulator, particularly its usefulness for analysis of systems with PV power generators.

II. PV ARRAY–INVERTER ASSEMBLY

The PV array–inverter assembly consists of a PV array and an inverter used to perform dc-ac energy conversion. In an autonomous energy system, the inverter can work in either master mode or slave mode. In master mode, the inverter controls the system’s frequency and voltage when there is no diesel generator on the system or the diesel is disconnected. The power exchange is determined by the system’s power balance. In slave mode, the user specifies the real and reactive power required to be generated or absorbed. The diesel generator or the grid handles the voltage and the frequency control. The transfer from slave mode to master mode (possible in an autonomous energy system) is determined based on the control strategy designed by the power plant designer or operator. Such a strategy can be easily programmed and, if justified by simulation results, modified to reach a desirable performance under specified load changes. The reader can find more details on possible performance of an inverter along with the description
of control mechanisms available to the user of RPM-SIM simulator in [17].

PV arrays are commercially available in modules. PV modules are used to build an array and their I–V characteristics are considered as I–V characteristics of the elementary PV array unit. In our model, we introduced a single solar cell as this elementary unit. Consequently, when setting up the simulation with commercial PV arrays, the user must declare a number of modules in one row or connected in series \( N_{\text{ser}} \), as well as a number of module rows connected in parallel \( N_{\text{par}} \). We represent a single cell characteristic by a two-column pv.map file. This ASCII file specifies the cell voltage and current under chosen temperature and insolation conditions. The representation of a cell for varying insolation levels and temperatures is accomplished using the scaling coefficients \( K_v \) and \( K_i \). The user can set these coefficients either as constants or make them functions of time. In addition, they can be applied as inputs to a special I–V CHAR CONTROL block, which automatically generates \( K_v \) and \( K_i \). This block contains the \( K_v\text{.map} \) file and \( K_i\text{.map} \) file, which implement \( K_v \) and \( K_i \) as functions of the insolation and temperature, respectively. These functions of two variables are represented at several points in the form of a two-dimensional table. The I–V CHAR CONTROL block uses interpolation and extrapolation to determine the values of \( K_v \) and \( K_i \) for temperature and insolation values not included in the table.

Fig. 2 represents the PV array module with the load current \( I_{\text{load}} \) input set by the inverter and the dc bus voltage \( V_{\text{bus}} \) set as the output voltage by the PV array module. The module’s operation is explained in Fig. 3 where the variables \( V_{\text{bus}} \) and \( I_{\text{load}} \), defined in Fig. 4 and set by the load characteristic, correspond to the maximum power condition, which occurs at the knee of the I–V characteristic as illustrated in Fig. 5. In Fig. 3, scaling coefficients \( K_v \) and \( K_i \) are shown as generated for any temperature-insolation pair, which may vary with time as in the simulation example presented below. For base temperature-insolation conditions, a two-column pv.map file represents a single-cell I–V characteristic. The input scaled voltage for this file

\[
V = \frac{V_{\text{bus}}}{N_{\text{ser}}} (1 + K_v)
\]

results in a current \( I \) and the scaled current

\[
I_{\text{cell}} = I + K_i.
\]

As shown in the lower part of Fig. 3, the dc-bus voltage is defined by the following equation:

\[
V_{\text{bus}} = \frac{1}{C} \int (N_{\text{par}} I_{\text{cell}} - I_{\text{load}}) dt.
\]

The I–V characteristics for a number of the commercial PV modules under adjustable environmental parameters such as temperature, beam irradiance, diffuse irradiance, wind speed, site altitude, sun elevation, angle of incidence, and others (along with the manufacturer’s module parameters) can be obtained using the Sandia IV Tracer Program. Using these data (for a particular solar module involved in the simulated system), we can generate the files \( K_v\text{.map} \) and \( K_i\text{.map} \) as described above, which are required by the I–V CHAR CONTROL block. We illustrate the steps involved in this with the following example.

1) Example: Using the Sandia IV Tracer Program, we selected a PV module (model ASE-100-ATF/17, ASE Americas, Inc.). Next, we set the following base conditions: ambient temperature at 25 °C, total irradiance at 50 mW/cm², sun elevation at 90°, angle of incidence at 0°, site altitude at 1600 m,
Fig. 6. Power balance of the system composed of a DG, a variable VL, and a preprogrammed PV array–inverter assembly operating in slave mode.

and wind speed 3 m/s. The corresponding I–V characteristic is shown in Fig. 5. For this particular characteristic, the short-circuit current $I_{sc} = 3.17 \, \text{A}$ was assumed as a base value and denoted $I_{scb}$, and the open-circuit voltage $V_{oc} = 19.13 \, \text{V}$ was assumed as a base value and denoted $V_{ocb}$. The files $K_v$.map and $K_i$.map contain values of $K_v$ and $K_i$, respectively. These values were determined for several ambient temperature values and several total irradiance or insolation values. The required values of $I_{sc}$ and $V_{oc}$ were determined by generating the I–V characteristics (for all temperature-irradiance pairs, for which $K_v$ and $K_i$ are included in the files $K_v$.map and $K_i$.map) using the Sandia IV Tracer Program. To determine elements of these files, we use the following equations:

$$K_v = \frac{V_{ocb}}{V_{oc}} - 1,$$

$$K_i = I_{sc} - I_{scb}.$$

To represent $K_v$ and $K_i$ as functions of two variables—temperature and irradiance—we use VisSim’s map block with the interpolate action and extrapolate action.

III. INTERACTION OF THE PV ARRAY–INVERTER ASSEMBLY WITH POWER SYSTEMS

The inverter simulated is a voltage source inverter capable of generating constant frequency and constant voltage on the grid side. In the simulation, we assumed that only the fundamental components of the voltage and current exist.

For a hybrid power system with a PV array–inverter assembly, a diesel generator, and a village load, the inverter acts as a slave. In this system, the diesel generator is connected to the grid and regulates the frequency and the voltage. We also can consider a power system with a PV array–inverter assembly and a village load. In this system, the inverter output controls frequency and voltage. The inverter acts as a master. Both of these systems are presented as case studies.

We also can consider a power system with a diesel generator, a PV array–inverter assembly, a village load, and possibly a wind turbine, in which it makes sense to switch the master function between the diesel generator and the PV array–inverter assembly. In this case, the following states describe the instantaneous system operation:

STATE 1: Inverter as a master (controls voltage and frequency; the DG is disconnected).
STATE 2: System started with the DG as the master (the inverter operates as a slave).
STATE 3: The DG synchronization starts and is followed by switching the master function to the DG.

If we start with the DG as a master and turn it off and on, we have the following sequence of states:

STATE 2, STATE 1, STATE 3, STATE 1, STATE 3, ...
STATE 3, STATE 1, STATE 3, ...

When we start with the inverter as a master (DG off), then turn the DG on and off, we have the following sequence of states:

STATE 1, STATE 3, STATE 1, STATE 3, STATE 1, STATE 3, ...

The user must program the required sequence of state switching using the programming/monitoring guide that comes with the simulation package. In both States 2 and 3 (and when the DG is controlling voltage and frequency), the user can additionally program the commanded values of the inverter’s real and reactive reference power. Note that in the initial stage of State 3 the inverter must retain the master function because the DG must be synchronized to the inverter-controlled grid.
Before taking over as a master. It does not happen automatically. To synchronize the DG to the grid, the following aspects must be in place.

- Voltage magnitudes must be equal.
- Frequency must be same as the grid frequency.
- Phase angles must be equal.

The DG remains unloaded during the synchronization process until the required conditions are met. This, in turn, results in loading or activation of the DG and the inverter is switched to the slave mode.

Switching to State 1 (with the inverter in the master mode and the DG disconnected) happens automatically. However, we must also make the DG ready to become a master when the next switching is commanded. In other words, we keep the DG idling, which is achieved by freezing certain variables of the simulated model.

IV. CASE STUDIES

A. Case Study 1

The system consists of a diesel generator as a master, a PV array–inverter assembly and a village load. The village load, as well as the real and reactive power provided by the PV array–inverter assembly, is preprogrammed and varies during the simulation. The diesel-generated power has to balance the power in the system. We illustrate this with the simulation results shown in Fig. 6. In this figure, the only visible inertia is that due to the mechanical time constant of the diesel generator. Because the dc power generated by the PV array is converted to ac power by the inverter, there is no visible inertia in this conversion process.

B. Case Study 2

The system consists of a PV array–inverter assembly with the temperature and insolation levels given as functions of time and a variable village load. The inverter controls frequency and voltage and balances the power in the system. The temperature and insolation levels represent the real data recorded on July 10, 1999, in Golden, CO. However, the time scale was changed by a proper declaration in the VisSim’s import block. Because of time scaling, the simulation period of 30 s actually corresponds to the real period from 4:00 A.M. to 8:40 P.M. The PV array is the only power source in this system. Therefore, to avoid meaningless transients, the village power is set to zero during the early morning and evening hours when insolation is very low. In this case study, we use a real PV array, which is the 20 × 20 array model ASE-100-ATF/17. The simulation results are self-explanatory and are shown in Fig. 7.

V. COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

In this section, we present the experimental data recorded for a power system that included the diesel generator (DG) with a 60-kW synchronous generator Model E7201L1, an AOC wind turbine (WT, Atlantic Orient Corporation), a PV–inverter assembly with PV panel Model ASE-100-ATF/17, a damp load (DL), and a village load (VL). The diesel generator operated as a master controlling frequency and voltage and the PV–inverter assembly operated as a slave providing real power of 30 kW. The single-line diagram of this system is exactly like the one in Fig. 1.
The data recorded over 10 s with a sampling period of 0.01 s included real and reactive power files for all these modules, as well as the line-to-line voltage file and the frequency file.

The same system was simulated using the RPM-SIM simulator, and the same data were recorded. In Fig. 8, we present corresponding experimental and simulated real power traces for both generated and consumed power. These are the cumulative plots, i.e., the real power generated includes power generated by DG, WT, and PV, and the real power consumed represents both VL and DL. Initially, particularly for frequency traces, there is a discrepancy period of approximately 2 s, which is the startup time of the diesel generator in the simulation. After that period, the simulated power and frequency traces closely follow the traces recorded.

Considering a slight oscillatory power imbalance of the recorded data (shown in Fig. 8) and the smoothing involved in the measuring system, there is very good agreement of the traces recorded and those obtained from the simulation.

VI. CONCLUSION

In this paper, we gave a short introduction to power generation systems with PV power generators both in grid-connected and stand-alone applications. This was followed by a presentation of research papers reporting essential results. We discussed abilities of the RPM-SIM simulator to analyze stand-alone renewable energy systems that include PV array–inverter assemblies. We developed this modular simulation system to study applications and cost-effective performance of renewable energy systems, analyze both static and dynamic performance, develop control strategies, and simulate autonomous renewable energy systems under different generation and load conditions (such as different wind speeds, temperature, insolation conditions, and load profiles).

The PV array–inverter assembly is an important part of the power system both for grid-connected and isolated operation. We discussed its interaction with power systems. It is apparent that the PV array–inverter assembly has the ability to balance the energy, and supply good power quality to the power network.

In Section V, we presented experimental results on a practical system and we compared those results to the simulation results. This comparison demonstrates good performance of the simulator and confirms the usefulness of the proposed simulation approach to the development of renewable energy systems. The simulator RPM-SIM is available on the National Renewable Energy Laboratory Web page (http://wind.nrel.gov/designcodes/simulators/rpmsim/).

REFERENCES


