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A software application for energy flow simulation of a grid connected photovoltaic system

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ABSTRACT

A computer software application was developed to simulate hourly energy flow of a grid connected photovoltaic system. This software application enables conducting an operational evaluation of a studied photovoltaic system in terms of energy exchange with the electrical grid. The system model consists of a photovoltaic array, a converter and an optional generic energy storage component that supports scheduled charging/discharging. In addition to system design parameters, the software uses hourly solar data and hourly load data to determine the amount of energy exchanged with electrical grid for each hour of the simulated year. The resulting information is useful in assessing the impact of the system on demand for electrical energy of a building that uses it. The software also aggregates these hourly results in daily, monthly and full year sums. The software finds the financial benefit of the system as the difference in grid electrical energy cost between two simultaneously considered cases. One is with load supplied only by the electrical grid, while the other is with the photovoltaic system present and contributing energy. The software supports the energy pricing scheme used in Jordan for domestic consumers, which is based on slices of monthly consumption. By projecting the yearly financial results on the system lifetime, the application weighs the financial benefit resulting from using the system against its cost, thus facilitating an economical evaluation.

1. Introduction

A photovoltaic electrical energy generation system connected to the electrical grid is the cornerstone of a distributed generation scheme. It utilizes the clean and unlimited supply of solar radiation to help reduce demand on central power stations. Availability of solar energy generally coincides with highest demand for electrical energy during the day. For a building that uses a grid connected photovoltaic system the amount of energy withdrawn form (or added to) the electric grid during a certain time interval depends on the locally generated energy and the local electrical load. Economical value of the system depends both on its acquisition cost and the financial benefit resulting from its use during its operation lifetime. In addition to available solar radiation, energy generated by the system depends on its design and installation parameters.

Compared with experimental studies, computer simulation enables a relatively faster, more flexible and more cost-effective method of performing a study of a system. This software application closes the gap between features envisioned in a research project [1], and features provided by readily available software packages. The closest package to the requirements of that work is HOMER Micro-power Optimization Model [2], developed by the US National Renewable Energy Laboratory (NREL). HOMER simulates many types of energy generation technologies [3]. Like HOMER, the present software performs hourly simulation over a full year, uses linear mathematical models to represent energy conversion operation of the photovoltaic array and inverter, and calculates global hourly irradiation on titled surface from values on horizontal surface using method explained by Duffie and Beckman [4]. The present software exclusively simulates grid connected photovoltaic system and provides a dedicated user interface.

The present simulation software is distinctly different from HOMER by providing a set of new features as described herby. It allows the user to interactively control the progression of the simulation timeline in hourly, daily, and monthly increments besides full year runs. All relevant tabular results are updated at the end of these increments to enable the user to inspect the results before the end of simulation and observe changing accumulations. Simulated energy flow on an hourly basis is graphically displayed in amounts and directions on a schematic diagram of the system. The present software implements an optional generic technology-independent energy storage component with support of scheduled charging/discharging. It enables demonstrating use of storage in meeting peek demand in a grid connected configuration.

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The software determines savings (or revenue) resulting from the system by simultaneously calculating monthly electrical energy cost in two separate scenarios. The first is where the load is exclusively supplied by the electrical grid. The second is with the system present. The software supports the pricing scheme used in Jordan for domestic consumers which is based on slices of monthly consumption.

The electrical energy producing component of a photovoltaic system is the photovoltaic array. The array is composed of photovoltaic modules. Each such module in turn is a collection of interconnected photovoltaic cells that convert radiation energy of sun rays into electrical energy [5]. A Photovoltaic array output is in the form of Direct Current (DC) electrical energy, which needs to be converted to Alternating Current (AC) form to be usable by typical electrical loads. This form conversion is the function of the Inverter [6]. Contrary to a stand-alone photovoltaic system, a grid connected photovoltaic system always has a connection to the public electricity grid [7]. An energy balance of the electrical load amount at any time interval and the AC energy provided by the inverter determines the amount of electrical energy drawn from the electrical grid. At times when inverted photovoltaic energy exceeds electrical load the excess is injected into the electrical grid.

Usually the highest levels of solar radiation during the day coincide with maximum demand on the utility electrical grid, which makes a photovoltaic system additionally beneficial to the electrical grid by reducing peak demand. Usually, grid connected photovoltaic systems do not employ a local energy storage device due to unjustified cost. Nevertheless, a further improvement on the demand curve is anticipated by incorporating such device.

Installing a grid connected photovoltaic system on a building reduces the monthly electrical energy bill and may even produce a net income to the investor. The economical question is whether the system financial benefit justifies the investment in its installation. The answer depends on a cost–benefit analysis that considers system cost and the applied energy pricing scheme.

2. System modeling overview

The present software simulates the grid connected photovoltaic system as being composed of the following components; photovoltaic array, DC/AC converter, electrical load connection, grid connection and an optional energy storage device. A schematic diagram of the simulated system is displayed in Fig. 1 [1]. Arrows show possible energy flow directions. Energy may flow from the AC bus to the DC bus only when storage is present. An energy balance at the DC and AC buses ultimately determines the flow of energy from (or into) the electrical grid.

The system components are modeled as black boxes that accept input energy, and produce output energy. The inner workings of these components in terms of electrical quantities are hidden. The component models are approximated as linear energy conversion functions between input and output energy.

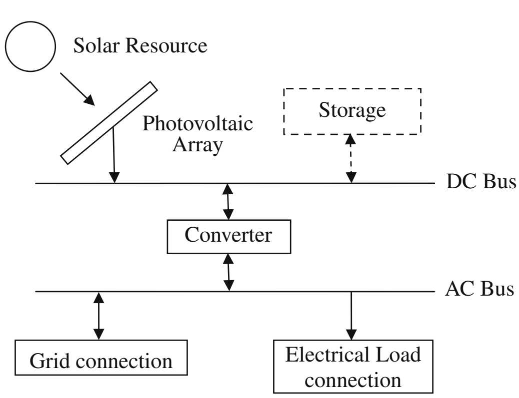

Fig. 1. Schematic diagram of the simulated system.

Average power P_{av}, corresponding to net energy E_{net}, flowing into or out of a component during a time step Δt, of one hour is given as follows:

$$P_{av} = \frac{E_{\text{net}}}{\Delta t} \tag{1}$$

2.1. Photovoltaic array

A linear conversion model implemented in HOMER and described in [3] is used in the present software. This model directly relates power output of the photovoltaic array P_{pv}, to incident solar irradiance G_T, according to the following equation:

$$P_{pv} = f_D C_{pv} \frac{G_T}{G_{TS}} \tag{2}$$

where C_{pv} is the photovoltaic array rated generation capacity. f_D is a de-rating factor which roughly accounts for long-term power reducing factors. G_{TS} is the incident irradiance at standard conditions and is equal to 1 kW/m^2.

For a given incident solar irradiation of I_T, during a Δt of one hour, the corresponding average irradiance G_T is given by:

$$G_T = \frac{I_T}{\Delta t} \tag{3}$$

From Eqs. (1)–(3) the energy E_{pv}, produced by photovoltaic array during one hour is given as:

$$E_{pv} = f_D C_{pv} \frac{I_T}{G_{TS}} \tag{4}$$

2.2. Converter (inverter/rectifier)

The present software approximates DC/AC inversion and rectification through linear energy conversion. Hence for the inverter, for each simulated hour time step, the inverter output AC energy $E_{inv,AC}$, is given by:

$$E_{inv,AC} = \eta_{inv} E_{inv,DC} \tag{5}$$

where $E_{inv,DC}$ is the inverter input DC energy, and η_{inv} is the inverter efficiency. Similarly, the rectifier output DC energy $E_{rec,DC}$, is given by:

$$E_{rec,DC} = \eta_{rec} E_{rec,AC} \tag{6}$$

where $E_{rec,AC}$ is the rectifier input AC energy, and η_{rec} is the rectifier efficiency.

2.3. Energy storage

A controlled addition or retrieval of energy from storage during a certain hour time step is the driving function of the storage component. It can be thought of as a battery with a charger/discharger. The storage component is defined by usable energy storage capacity, maximum rates of addition or retrieval of energy, and time duration for these operations.

Starting with an initial energy content of $E_{s,0}$ at the beginning of a simulated hour, if the storage component undergoes charging then its energy content E_s at the end of that hour is given by:

$$E_s = E_{s,0} + \eta_c E_c \tag{7}$$

where E_c is the charging energy at the component terminals, and η_c is the charging efficiency. On the other hand, if it undergoes