MODELLING OF PHOTOVOLTAIC ENERGY GENERATION SYSTEMS

Pekka Ruuska
Antti Aikala
Robert Weiss
VTT Technical Research Centre of Finland
P.O.Box 10000, FI-02044 VTT, Finland
E-mail: pekka.ruuska@vtt.fi

KEYWORDS
APROS, Dynamic simulation, Modelling, Photovoltaic, Solar power.

ABSTRACT

We present the development of a dynamic software simulation environment for modelling small and large scale photovoltaic (PV) energy generation systems. The model elements of solar panels, Maximum Power Point Trackers (MPPT) and solar inverters were integrated to a simulator system providing weather and power grid models as well as simulation of combustion power plants. The integrated system enables accurate dynamic simulation of complicated energy processes that utilize a variety of technologies. We tested our model against a large scale solar photovoltaic plant that produces energy to the power grid. The first test runs proved that the implemented models predict the produced energy adequately under constant irradiation.

INTRODUCTION

Simulation can help to maximize the generated photovoltaic energy and to optimize the design of wide solar panel systems. Furthermore, the simulation models can be integrated with models of other energy generation systems such as heat and power plants. Dynamic simulations provide tools for aiding the design work, optimization, accident analysis and control development of power generating systems. They can advance energy-efficiency, reduce greenhouse gas emissions and cut costs of producing energy in complicated industry processes.

We developed a software environment for modelling photovoltaic panels, maximum power point trackers (MPPT) and solar inverters. These were integrated to APROS, which is a widely used dynamic process simulator. APROS provides weather models, power grid simulation as well as detailed and accurate modelling of combustion power plants.

This paper describes calculation principles, design and implementation of the new models. First test runs and comparison to a real PV energy generation system is presented. These simulations were done in the EuroEnergest project, funded by the European Union's 7th Framework Programme. Among the goals of that project is to reduce energy consumption in car industry through exact and predictive control of on-site energy production processes.

THE APROS ENVIRONMENT

APROS offers tools, solution algorithms, and model libraries for the full-scale modelling and simulation of dynamic processes. APROS was developed by VTT Technical Research Centre of Finland and Fortum Corporation. It can be utilized e.g. in the transient modelling of various nuclear and combustion power plants, pulp and paper mills, fuel cells and several other energy systems. The process itself, as well as automation and electrical systems can be modelled, and real plant measurements can be implemented to APROS (Saarinen et al. 2007). APROS is currently developed for modelling the alternative and small-scale energy production systems.

MODELLING PHOTOVOLTAIC PANELS

As an electrical element a photovoltaic panel resembles a DC current source still its internal resistance is not constant; it varies non-linearly with solar irradiation. Typically the current produced by photovoltaic modules depends on irradiance and cell temperature while the voltage depends mainly on temperature (Figure 1).

Precise mathematical modelling of a PV cell requires determining physical characteristics, which are usually not provided in the solar panels' data sheets (Gow and Manning 1999). Strict models can also require utilizing complicated numerical methods in calculations. A solar cell can be modelled with a single diode model (Figure 2). At low irradiance a two diode model should yield more precise results. An additional parallel resistance may further advance the accuracy of the model at the expense of more complex calculations. In all models the mathematical difficulties arise from the p-n diode junction of the equivalent circuit as it must be analysed with an exponential equation (Sera et al. 2007).

Proceedings 28th European Conference on Modelling and Simulation ©ECMS Flaminio Squazzoni, Fabio Baronio, Claudia Archetti, Marco Castellani (Editors)
ISBN: 978-0-9564944-8-1 / ISBN: 978-0-9564944-9-8 (CD)

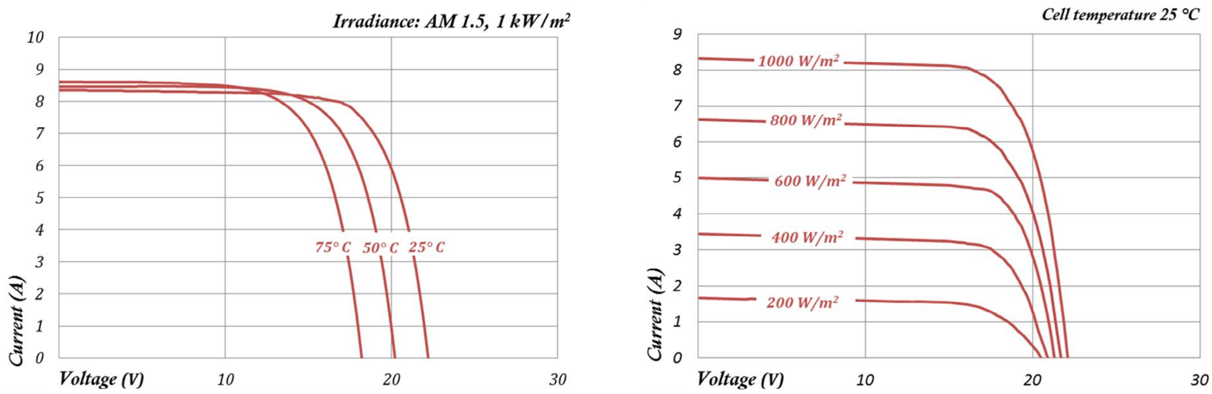
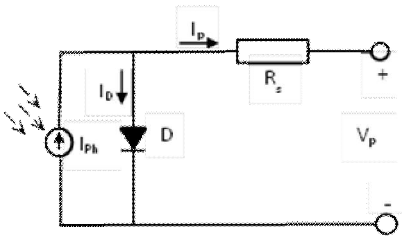


Figure 1: V-I Curve for A Typical Multicrystal Photovoltaic Module under 1,0 kW/m^2 Irradiation in Various Temperatures (on the left) and The Same Cell at T = 25° C under Different Radiation Intensities (Kyocera 2013)

However, as the electrical parameters of real solar modules always differ somewhat from the theoretical values, quite precise results from simulations cannot be expected. Also the electrical characteristics and the performance of solar panels slowly vary through their lifetime. The changes caused by ageing and soiling can be exactly monitored only through measuring. Furthermore, cloudiness and other weather conditions crucially affect the performance of a solar panel system and these factors are also difficult to predict or measure exactly. Therefore simplified models which do not produce quite accurate results in all conditions but which do not entail such impractical requirements, can be quite appropriate in simulation.



Figures 2: A Simplified Single-Diode Equivalent Circuit of a PV Module (Xiao et al. 2004; Bellini et al. 2009)

We implemented two different mathematical models to our simulation software. With the first model we can determine the output current and voltage under varying conditions from a solar panel's data sheet information (Bellini et al. 2009). We refer to this model as "Model 1" in this paper. The second model ("Model 2") is more accurate especially under low insolation, but it requires first measuring I_{SC} (Short Circuit Current) and V_{OC} (Open Circuit Voltage) under two different radiation intensities (Zhou et al. 2007). As we first ran the simpler model in our simulations and experiments, we do not describe in detail the second model in this paper.

A simplified linear formula for the I_{SC} of a photovoltaic cell is (Bellini et al. 2009):

$$I_{sc} = (G/G_0) \cdot [I_{SC0} + k_T(T - T_0)] \qquad (1)$$

where k_T is temperature coefficient for I_{sc} (in A/°C), G is solar irradiation and T is cell temperature while G_0, I_{SC0} and T_0 are the corresponding values under STC (Standard Test Conditions). The panel manufacturers provide temperature coefficients for Isc and Voc in their data sheet. The photovoltaic current Ip as a function of photovoltaic voltage Vp is determined by:

$$I_p = I_{SC}\,[1 - C_1(e^{(V_p/C_2 V_{OC})} - 1)] \qquad (2)$$

Where coefficients C_1 and C_2 are defined in Equations (3) and (4) and which depend on the parameters I_{SC0}, V_{OC0}, I_{MPP0} (Current at Maximum Power Point) and V_{MPP0} (Voltage at Maximum Power Point). Also these parameters are always presented in data sheets of PV panels.

$$C_1 = (1 - I_{MPP0} / I_{SC0}) \cdot e^{(-V_{MPP0} / C_2 \cdot V_{OC0})} \qquad (3)$$

$$C_2 = ((V_{MPP0} / V_{OC0}) - 1) / \ln(1 - (I_{MPP0} / I_{SC0})) \qquad (4)$$

It is shown in (Bellini et al. 2009) that from the above we get V_{OC} under radiation intensity G and in temperature T as follows:

$$V_{OC} = V_{OC0} + m_T(T - T_0) - \Delta V(G) \qquad (5)$$

where m_T is the temperature coefficient for V_{OC} (in V/°C) and $\Delta V(G)$ is a correction term obtained from:

$$\Delta V(G) = V_{OC0} - V_{OCm} \qquad (6)$$

in which V_{OCm} is the transposed open circuit voltage derived from yet another parameter $I_t(G)$ (transposed current) as follows:

$$I_t(G) = I_{SC0} \cdot [1 - (G/G_0)] \quad (7)$$

$$V_{OCm} = C_2 \cdot V_{OC0} \cdot \ln[1 + (1 - (I_t(G)/I_{SC0})) / C_1] \quad (8)$$

where G_0 is 1000 W/m^2 while C_1 and C_2 are defined in equations (3) and (4).

MODELLING MAXIMUM POWER POINT TRACKERS

Maximum power point trackers (MPPT) are used to maximize the output power from solar panels. The goal of the MPPT techniques is to automatically find the voltage V_{MPP} or current I_{MPP} at which the PV array (solar panel) should operate to obtain the maximum power output P_{MPP} under a given temperature and irradiance. Even a simple MPPT may yield an energy gain of 20% or up to 30% from a PV array; therefore they have become essential elements in PV systems today. An MPPT can be integrated to a solar inverter or to a battery charger or they can be installed as a separate element into a PV system.

Dozens of different algorithms to maximum power point tracking have been introduced (Esram and Chapman 2007). These can be implemented with various technologies. The algorithms perform differently when irradiation changes, some of them are better at low light and others may find the MPP quicker in steady conditions. Still the MPPT vendors usually do not publish the algorithms which they implement in their devices. Therefore we can present only approximations of the real characteristics of the MPPT devices that we simulate. However, already our first test runs indicated that our estimations were rather close to reality.

We chose two different algorithms to implement into our simulation model. These are the Incremental Conductance Method and the Fractional Open Circuit Voltage Method. Most of the newer and perhaps more sophisticated algorithms are based on these rather classic approaches. The first method is supposed to determine the MPP optimally and without oscillations while it may track in the wrong direction in some conditions. The second method never finds the exact MPP; still it is shown that the method works better than many others under low insolation (Esram and Chapman 2007).

In the first procedure the output voltage V is changed in steps ΔV and the resulting changes of output voltage and current I are measured. If the change in conductance $\Delta G = \Delta I/\Delta V$ is positive the output voltage is increased again until the change is zero. And if the first change in conductance is negative, the voltage is decreased until there is no change in conductance.

The second method is very simple, it requires only measuring the output voltage and factoring that with a constant. The constant is known (0.76 is typical) or it can be determined by measuring.

TEST RUNS AND RESULTS

Our first example illustrates generation of DC power with a photovoltaic system (Figure 3). On the left in the figure are the solar radiation and the irradiation processor modules that calculate the total amount of effective received irradiation on a tilted surface. The output voltage of the PV panel is controlled by the MPPT module which changes the voltage ratio of the DC/DC converter. The model calculates the produced power. The generated electricity is supplied to a battery or a DC load module.

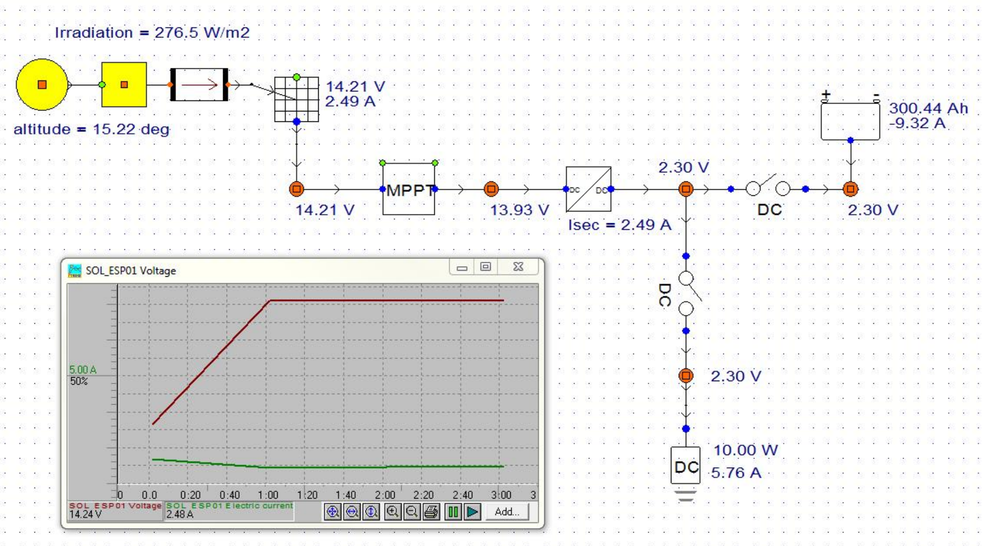


Figure 3: APROS Simulation of a Small-scale PV Energy Generation System

Examples of I-V curves calculated by using “Model 1” and the system in Figure 3 are depicted in Figure 4. It shows that at radiation intensity of 400 W/m^2 or more the discrepancy with the data sheet (Figure 1) curves is less than 2 % while at low irradiation it is close to 10%.

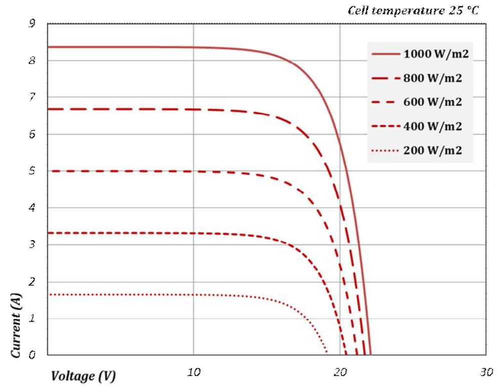


Figure 4: Calculated V-I Characteristics at Different Irradiancies with “Model 1”

After this we simulated solar PV energy production to the power grid by connecting solar panel modules in series with a MPPT, a DC/DC converter and an inverter to build up a “solar inverter” (Figure 5). In these simulations we utilized “Model 1” and the Incremental Conductance Method in MPP tracking (Esram and Chapman 2007). The reason for these selections was that we wanted to analyse the energy production potential of the system under high irradiation, when it is connected to the grid. “Model 1” is adequate for that purpose and it needs only the data sheet information as input, which facilitates the simulation.

In the first simulation run we kept the weather model’s parameters constant to analyse the accuracy of our photovoltaic cell, MPPT and solar inverter models (Figure 6). The tests indicated that our simulations can give rather close estimation of the energy produced at the site, if the weather conditions remain steady. The error between the measured and the calculated energy was about 2 % when the Sun was high and the local cloud conditions were consistent (Table 1). The cloudiness parameter of the APROS weather model was set to 0.45 indicating “partly cloudy” sky. Such cloudiness prevailed only between 10:30 and 11:30 on that day. From 11:30 to 14:00 the difference between the expected and measured energy varies from 3% to 10%. After 14:15 and up to 17:00 the discrepancy is about 6%. The inaccuracy is mostly explained by the changes in cloudiness. Another important factor is the low resolution of the measuring system; it provides the produced energy as kWh in 15 minutes which averages the peaks in produced photovoltaic energy.

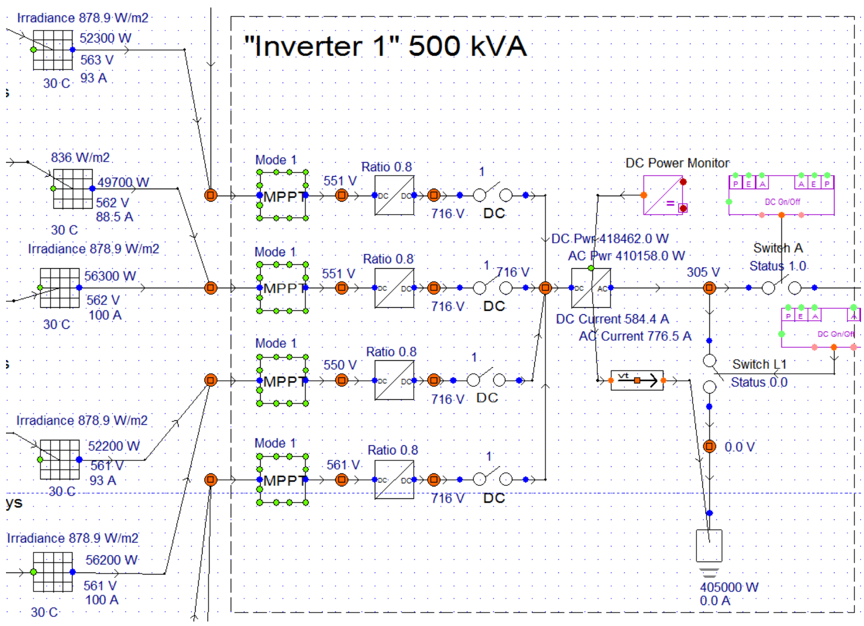


Figure 5: Part of a Model that Simulates a PV Production System Capable to 500 kW of AC Power.

In the morning hours, before 09:00 the sky was mostly clear and setting the cloudiness to 0.45 gave too low output voltage. There are also two further reasons for the clearly bigger differences between the measured and the calculated energy in the low light conditions. Firstly, the simple mathematical model employed in these tests may give a 10% error in those conditions (Bellini et al. 2009). Secondly, when the Sun is low on the horizon, the PV panels generate so low voltages (less than 500 V) that the solar inverters cannot be connected to the power grid. Therefore, when no load is connected, the simulation models of the electrical components do not calculate worthy results either.

Table 1: Comparison of Calculated and Measured Energy as kWh in 15 Minutes

Time	Measured	Calculated	Difference
10:30	296	290	–2.1 %
10:45	312	313	+0.2 %
11:00	329	334	+1.5 %
11:15	345	354	+2.5 %
11:30	363	372	+2.5 %
11:45	376	389	+3,4 %

In our second tests, publicly available weather information from Martorell was utilized. The cloudiness was mapped to the weather model as numbers between 0.10 and 0.55. In this case, the calculated energy differs from the measured production with an error varying from 2% to 7% (Figure 7).

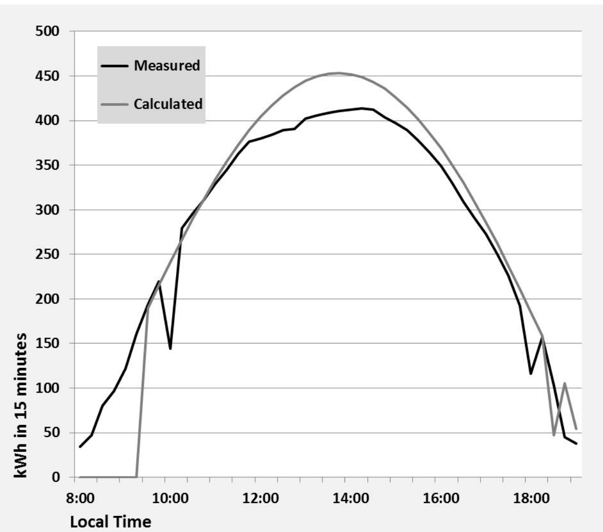


Figure 6: Comparison of the Measured and the Simulated Energy Produced on 10th July, 2013

Unfortunately, typical weather data describes cloudiness only as words; such as “scattered clouds”. And this information is given as average for 30 minute periods, while the received irradiation may rapidly vary on a wide scale. It is clear that the 30 minute intervals are too long for our tests (Hansen et al. 2102). In our example case, the biggest error is at 13:30, when the cloudiness changes from “partly cloudy” to “scattered clouds”. And there are other environmental factors such as local geography and site topology that affect the received irradiation. Quantified irradiation data can be provided with a local pyranometer, which we plan to utilize in the next phase of our project. Still we cannot expect that the accuracy of our models would radically advance as there are several uncertainties in the model. The total inaccuracy of our simulation is typical when compared to other PV energy yield simulations (Ransome 2008).

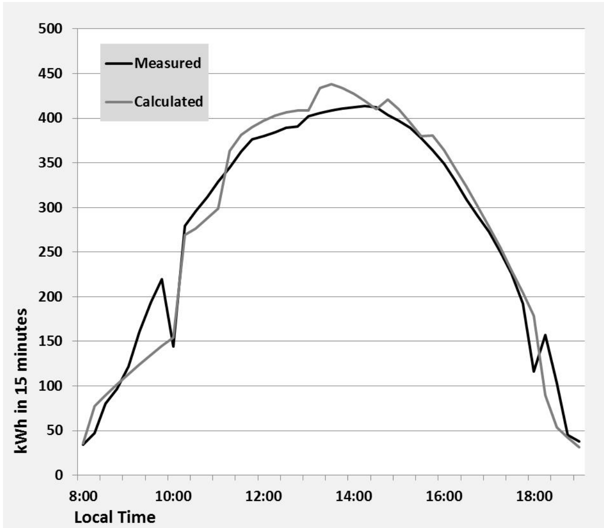


Figure 7: The Same Comparison as in Figure 6 when also the Changes in Cloudiness are simulated

CONCLUSIONS AND FURTHER WORK

Simulation models of PV cells, MPPT and solar inverters were implemented into APROS system and the first calculation results were compared against a real large-scale PV plant. The mathematical models were shown to produce adequately accurate results. However, more precise results can be expected, when more exact quantitative information about the weather conditions become available. One of the aims of the EuroEnergest project is to accurately forecast the total energy generation potential of the pilot plant. This requires modelling at least the solar PV systems, the on-site CHP plant, the boiler systems, the heat recovery system and the absorption chillers with APROS. The implemented model of the solar PV energy systems is sufficient for that purpose.

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AUTHOR BIOGRAPHIES

PEKKA RUUSKA received his M. Sc. degree in Electrical Engineering in 1980 and Licentiate of Technology (Computer Technology) in 1993 from the University of Oulu, Finland. From 1985 he has been working with VTT Technical Research Centre of Finland. He is currently a senior scientist and his research interests are energy efficiency and renewable energy systems. His e-mail address is: `Pekka.Ruuska@vtt.fi` and his Web-page can be found at `http://www.vtt.fi/?land=en`

ANTTI AIKALA received his M. Sc. degree in Forest Products Technology, in 2000 from the Helsinki University of Technology. He has worked as a researcher first in Keskuslaboratorio Oy, a research company for Forest industries in Finland, and from 2009 as a research scientist in VTT Technical Research Centre of Finland. He has worked in areas of simulation, statistical analysis and optimization in the field of dynamic systems and processes. His e-mail address is: `antti.aikala@vtt.fi` and his Web-page can be found at `http://www.vtt.fi/?land=en`

ROBERT WEISS was born in Nürnberg, Germany and went to Helsinki University of Technology, Finland, where he studied engineering physics and obtained his M.Sc. (Tech.) degree in 1993 and Licentiate (Tech.) degree in 2002. Since 1990 he has worked with energy and environment field with research, IT, simulation and management topics for Energy Consultancy companies, VTT Technical Research Centre of Finland, ABB Ltd, and Process Vision Oy. Since 2010 he is managing and co-ordinating Smart Energy Grid related research and simulation projects at VTT Technical Research Centre of Finland. His email address is: `Robert.Weiss@vtt.fi` and his Web-page can be found at `http://www.vtt.fi/?land=en`