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Complex method for performance prediction of photovoltaic systems

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Abstract. This paper shows a method for modelling photovoltaic (PV) systems, including different models for the solar cells, DC circuit and the inverter. The author created a Matlab simulation based on these models, enabling to perform various calculations. Predicting the amount of energy produced by PV systems has a great impact on the accurate calculation of financial return of investment. Furthermore the more accurate estimation of produced energy promotes the system integration of small-scale PV generators by enabling to schedule their production. The different analyses shown in this paper helps to understand the operation characteristics and the most important design considerations of these small-scale solar plants.

Key words

PV systems, modelling, simulation, energy production prediction

1. Introduction

The PV units convert solar energy directly into electric energy. Recently the installed PV capacity shows a significant worldwide growth, but still represents only a very small fraction of the total electricity production in Hungary. The main limiting factors are the high investment costs and the resulting long payback period. An important part of the payback calculation is the prediction of the expected revenue, which is closely related to the energy production of the PV plant, therefore the precise prediction of the solar energy production is particularly important.

The main task of the solar system's model is to calculate the performance of the system as a function of solar radiation and ambient temperature. For the calculation of long-term energy production these data are available from meteorological databases containing the averages of measured data of preceding years. Since the meteorological data can be considered accurate in the long term, therefore our model is also accurate. For short-term predictions it is only possible to get meteorological data from moderately reliable weather forecasts, therefore the accuracy of the model has only secondary importance in this case.

2. Models

The models introduced in the paper use only data, which is easily accessible on the data sheet of most devices, so the models can be easily applied for any possible system. The models should provide the most accurate results with the least complex and time-consuming calculations: if these conditions are unachievable with one model, then either two different models were created for the different requirements, or there is an option to neglect some less important effects.

A. Solar cell model

One of the simplest methods to calculate the solar cell's power can be seen in (1)[1].

$$\boldsymbol{P_{mp} = P_{STC} \cdot \frac{G}{G_{STC}} \cdot \left[1 + \mu_{P,mp} \cdot (T_c - T_{c,STC})/100\right]} \quad (1)$$

Where P_{mp} is the maximum module power (W), G is the global solar radiation (W/m^2), T_c is the cell temperature (°C), $\mu_{P,mp}$ is the temperature coefficient of P_{mp} (%/°C) and the STC subscript stands for Standard Test Conditions. This model has low computation requirement, it takes the cell temperature's effect into account. On the other hand it applies only to the maximum power point (MPP) and it cannot compute the voltage nor the current, and it neglects the radiation dependence of the efficiency.

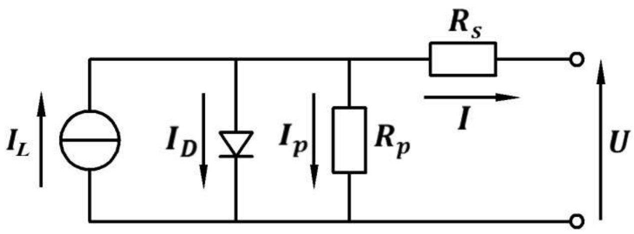

Fig. 1. Equivalent circuit of a solar cell

A more accurate model can be created by obtaining the module characteristics from the solar cell equivalent circuit shown in the Figure 1. The charge separation caused by the absorbed light can be modelled by a current source, the diode represents the recombination occurring on the p-n junction and the real cell's internal losses can be taken into consideration as resistances. Equation (2) can be written based on the equivalent circuit [2].

$$\boldsymbol{I = I_L - I_0 \cdot \left(exp\left(\frac{q(V + I \cdot R_s)}{n \cdot k \cdot T_c}\right) - 1\right) - \frac{(V + I \cdot R_s)}{R_p}} \qquad (2)$$

Where I and V are the current (A) and voltage (V) of the solar cell, I_F is the light current (A), I_0 is the diode saturation current (A), q is the charge of an electron (C), n is the diode ideality factor, k is the Boltzmann constant (J/K) and R_s and R_p are the series and parallel resistances (Ω). The parallel resistance was neglected, since it has only a very small effect on the cell characteristics. Let us use Townsend's [3] equations to determine the reference values of the unknown parameters, their radiation and cell temperature dependence. Knowing these values it is possible to define the I-V and P-V characteristics of the solar modules using any type of numerical methods.

This model is more complex and accurate than the simple one shown above. Using the characteristics it is possible to calculate the power, current and voltage of the module at any operating point. This model also includes the radiation and temperature dependence of the efficiency, the only disadvantage is the numerical calculation's significant time requirement.

The meteorological databases contain only radiation and ambient temperature, so it is necessary to compute the cell temperature required in both models. According to the law of energy conservation, and using the Nominal Operating Cell Temperature (NOCT) measured by the manufacturer, the cell temperature can be estimated by (3)[4].

$$\boldsymbol{T_c = T_a + \frac{G}{G_{NOCT}} \cdot (T_{NOCT} - T_{a,NOCT}) \cdot \left(1 - \frac{\eta}{\tau\alpha}\right)} \qquad (3)$$

Where T_a is the ambient temperature (°C), η is the module efficiency, τ is the transmittance of the glazing and α is the absorptance of the module. The efficiency dependant on the cell temperature; therefore (3) cannot be solved analytically, only by numerical iteration.

B. DC circuit model

To model the DC circuit we only need to know the number of solar modules connected in series and parallel and the parameters of the connecting cables. The model calculates the input voltage and the power of the inverter considering the power losses and voltage drops.

C. Inverter model

The first task of the inverter model is to compute the losses occurring on the device. These losses depend on the input voltage and power of the inverter. The losses as a function of the DC power was estimated with a second-degree polynomial fitted to the measured points of the manufacturer. At a constant voltage the losses on the shunt elements are constants, the loss on the switching elements is nearly proportional to the transmitted power and the losses on the series elements are proportional to its quadrat. Lacking sufficient measurement data, the voltage dependence of the losses was calculated using linear interpolation. To predict the annual energy production we can also use the European efficiency of the inverter, which is easier than the detailed loss calculation.

The other task of the inverter is to detect the unreachable operating points. When the MPP of the solar modules exceeds the input power or voltage limits of the inverter, the solar cells have to operate in another operating point with lower power output. The model should detect these cases and calculate the actual achievable power.

Using the above presented model a simulation program was created in Matlab, which can perform the required calculations. This simulation is able to compute many different results for any possible photovoltaic systems.

3. Simulation results

A. PV efficiency

The simulation can be used to calculate the efficiency of solar modules as a function of the cell temperature and solar radiation using the most complex and accurate model, the result can be seen in the Figure 2. These plots graphically represent the PV's efficiency for various weather conditions, which shows what proportion of the given irradiation can be converted into electricity.

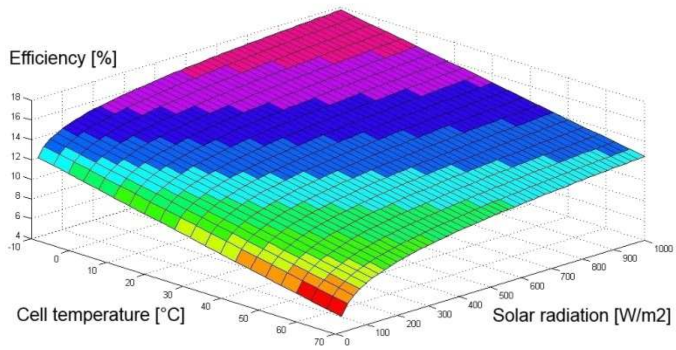

Fig. 2. Efficiency of the examined solar module

The efficiency decreases linearly with increasing cell temperature, which corresponds to the expected dependence based on the previously shown simple modelling method using the temperature coefficients published by the manufacturers. The efficiency is also a very nonlinear function of solar radiation. Although the radiation's effect has approximately the same magnitude as the temperature's, the radiation dependence cannot be described with the simple model due to nonlinearity and the lack of sufficient data from the modules' data sheet. The STC data refers to 1000 W/m^2 radiation, which can be considered the maximum in our climatic conditions, therefore neglecting the radiation dependence almost always causes to overrate the module power. The relative error is even bigger with decreasing radiation, but the absolute error has a maximum on the medium radiation level, where it can exceed 10 W in the case of a common module with 250 W_p power.

The reasons of the changing efficiency were also examined, which showed a very tight correlation between the MPP efficiency and the MPP voltage. According to the simulation results, the ratio of short circuit and MPP current is approximately constant, while the short circuit current is also proportional to the radiation [3], the voltage is the only factor affecting the efficiency in (4). The changes in voltage can be explained with the previously shown equivalent circuit and characteristic: the temperature's effect is realised by the threshold voltage of the p-n junction, while the radiation's effect comes from the shape of the I-V curve.

$$\boldsymbol{\eta_{mpp}} = \frac{P_{mpp}}{G \cdot A} = \frac{I_{mpp} \cdot U_{mpp}}{G \cdot A} \qquad (4)$$

In practical calculations the input data are the solar radiation and the ambient temperature, the cell temperature is only a derived value. Figure 3 shows the PV module efficiency as a function of ambient temperature and radiation.

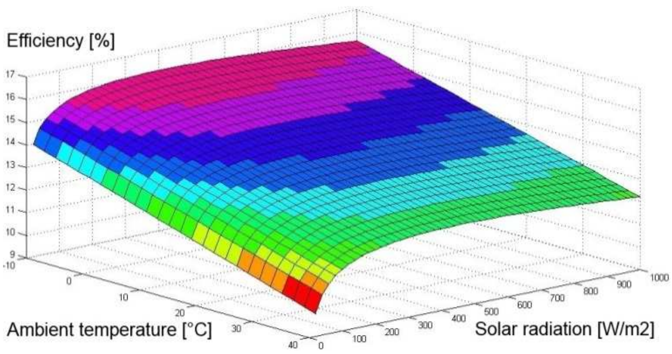

Fig. 3. Module efficiency as a function of meteorological data

The most significant difference from Fig. 2 is the decrease of efficiency at the higher radiation range, which is caused by the more intense warming of the cell. Keeping the ambient temperature constant the higher radiation leads to higher cell temperature, which reduces the efficiency and together with the previously seen increase they result in a maximum at the medial 300-500 W/m^2 radiation. This means that in case of a given annual irradiation level the PV module works the best by colder air temperature and medium solar radiation, of these two the latter is typical in Hungary.

The efficiency of the whole PV system is also affected by the losses occurring on the DC bus and on the inverter, where the inverter's losses are dominant. The relative value of the system losses has its minimum at medium radiation, which enhances the attributes derived from the PV modules. The complete system efficiency, which refers to the AC power fed into the grid, is shown in Figure 4. It is very similar to the module's efficiency, aside from the bit lower values due to the power losses and the very low radiation range, where the constant losses of the inverter largely reduces the efficiency.

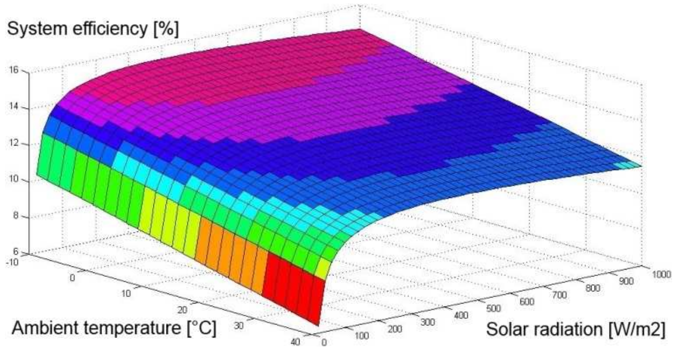

Fig. 4. Efficiency of a PV system

B. Annual energy production

Predicting the annually produced energy is very important for payback calculations, where the PV plants' incomes come from the generated electricity. This is also an important comparison criterion between the different PV systems, since it contains the effect of the different meteorological conditions with the weight appropriate to their occurrence.

Two different meteorological databases were used for the calculations. One of them is the Photovoltaic Geographical Information System (PVGIS) made on behalf of the Joint Research Centre of the European Commission [5]. It contains only one average day's solar irradiance in every month with one temperature-radiation data pair in every 15 minutes. The other database called "Meteo" was obtained from the demo version of the PVsyst software [6], and it contains hourly data for every 8760 hours of the year. The average values of the PVGIS database smooth the effect of the immoderate weather conditions, therefore the Meteo database is considered the more accurate.

The calculations were performed to a site near the Hungarian city of Debrecen (47°29'25"N, 21°35'59"E). The examined system consists of 30 PV modules in two strings with equally 15-15 module in each, and an appropriate solar inverter. BOSCH c-Si M60 250 monocrystalline solar panels are used with 250 W_p peak power each that means a total DC power of 7.5 kW_p. The chosen inverter is a Fronius IG Plus 60 V-1 transformer inverter with 6 kW nominal AC power output, which is an ideal choice for the solar panels considering the losses and the typical moderate solar radiation.

The annual solar irradiation slightly differs in the two databases: its value is 1490 kWh/m^2 based on the PVGIS but 1535 kWh/m^2 using the Meteo data, which difference may be caused by the different measurement years or different methods used while creating the database. Due to this nearly 3 % irradiation difference 3 % more energy production can be expected in case of the calculation based on Meteo. Table I. contains the major simulation results with both databases, and the relative difference between the results, considering Meteo as the reference.

Table I. Annual energy production simulation results

Database	PVGIS	Meteo	Difference
Annual PV energy [kWh]	10409	10582	-1.63 %
Annual AC energy [kWh]	9837	9979	-1.42 %
Average PV efficiency [%]	14.167	13.985	1.30 %
Average AC efficiency [%]	13.389	13.188	1.52 %
Annual system losses [kWh]	572	603	-5.24 %
Average DC voltage [V]	429	416	3.28 %

The annual PV energy means the DC energy produced by the solar cell, while AC energy refers to the energy fed into the grid. The PV and AC efficiencies can be interpreted in a similar way, the system losses containing the losses on DC circuit and inverter, while the DC voltage is the input voltage of the inverter. The energy production surplus in the case of Meteo is lower than the expected 3 %, which indicates that the efficiency is higher using the PVGIS database. The higher power can be explained using the PVGIS's average, typically medium radiation data, which cause the better efficiency values according the formerly presented Figure 4. Although this 1.5 % difference is not very significant, it shows that the selection of the proper database also influences the accuracy of the energy production prediction.

The simulation results were validated by comparison with an other PV estimation software. In order to eliminate the errors caused by the different databases, the same programs were used for validating from which the databases were derived: the PVGIS website's "PV Estimation" function and the PVsyst software. The differences between the results of the simulation introduced in this paper and the independent sources were sufficiently small, lesser than 1.2 % in all examined cases.

The proportion of the system losses according to the Meteo calculation is 5.7 %, which consist of the 0.45 % loss on the DC wiring and the 5.25 % loss on the inverter. In common cases the inverter's losses are one order of magnitude higher than the DC circuit's, so the system losses depend on the efficiency of the inverter.

The specific energy production of the PV array, defined as the produced energy divided by the peak power of the modules were also computed, its value is 1330 kWh/kW_p in the presented case, which is equivalent to a 15.2 % capacity factor. It is important to note that these values depend largely on the available solar irradiation beside the specification of the PV system.

C. Choosing optimal inverter power

Choosing the appropriate inverter to the PV array is very important for the optimal operation of the system. To ensure the maximum energy production the solar modules should always operate in the MPP, which implies that the operating range of the inverter contain the MPP under all practical circumstances. While one module's MPP voltage depends on the weather conditions, the input voltage of the inverter can be adjusted with the number of modules connected in series. The module's nominal voltage applies for the STC, the actually implemented MPP voltage is lower than this value in most of time. In case of the PV system presented in the previous chapter the total nominal MPP voltage of the 15 series modules is 455 V, while the average DC voltage is only 416 V according to Table I. This effect always should be taken into consideration in the determination of the proper number of modules per string.

Choosing the suitable inverter in the aspect its maximum input power is a complex optimization task. Since the module's nominal power is not a theoretical maximum but only a reference, higher MPP power can also occur, therefore the constant operation in the MPP cannot be guaranteed even in the case of equal inverter and array nominal power. Due to the typically lower radiation values the modules operate only in a small part of the year over or near their nominal power, thus from an economic point of view it is not so important to insist to the maximum energy production. Using an inverter with lower maximum input power than the module's peak power causes losses in the produced energy but reduces the investment costs as well. Figure 5 shows the percentage of the energy production reduction as a function of the power limit's relative value.

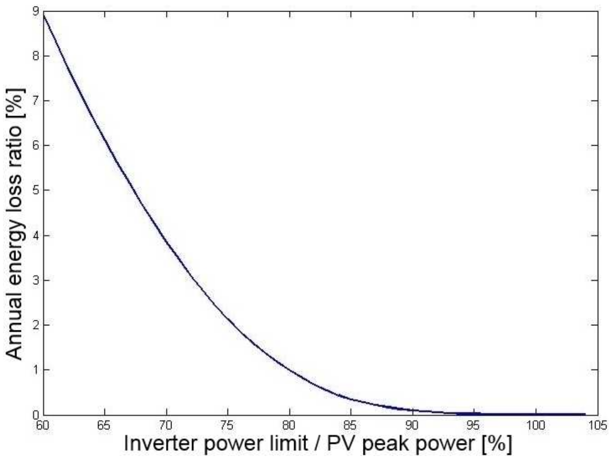

Fig. 5. Losses caused by the undersized inverter

It is important that the power limit means the maximum input power of the inverter, which is usually about 5 % higher than its nominal power, where the difference covers the internal losses. Over 90 % power limit ratio the occurring losses are negligible, by 80 % they are about one percent, while lower power limit results a quick increase in energy losses. These specific values belong to the Hungarian weather conditions, but the shape of the curve and the used concept are similar everywhere in the world.

The optimal inverter power in addition to the energy losses also depend on the feed-in tariff, the investment cost savings and expected lifetime of the inverter. The cost saving generally comes from the price difference of the inverters with different nominal power, but it may be also due to the different grid connection costs depending on the rated power of the power plant. More complex methods also exist for the best inverter sizing [9], but as a rule of thumb in practical applications 80 % is acceptable for an optimal value of the inverter and PV array power ratio.

D. Simplification possibilities

Accuracy and fast calculation are also important in the prediction of energy production. In the long-term prediction used for payback calculations the meteorological databases are statistically accurate, so the precise modelling is essential. However, the long-term calculations are performed only a few times during the design of the PV system, thus slower calculation is also sufficient. By short-term predictions the considerations are reversed: due to the inaccurate meteorological forecasts and the frequent or real time calculations a simpler but faster model is favourable.

Several simplification methods have been presented in the second chapter of this paper, of which quantified indicators are shown below. Using the European efficiency in the inverter model instead of the momentary efficiency depending on the operating status is a quite good approximation for annual calculations. In the case of the previously presented PV system 5.25 % inverter losses belong to the inverter's 95 % EU efficiency, which is a negligible difference. Since the EU efficiency is an annual average, using it in short-term calculations relating only to one specific operating condition can cause higher inaccuracy.

The cell temperature according to (3) normally can be calculated with iteration, which could be avoided only by neglecting the cell temperature's efficiency dependence represented by the last bracketed factor. This speeds up the calculation but causes the underestimation of the MPP power. The relative error increases proportionally with the radiation and exceeds 2.5 % at 1000 W/m^2, thus the absolute error is proportional to the radiation's quadrat. In annual calculations the predicted energy with this simplification is about 1.5 % lower than the accurate result.

The most significant simplification is the simple PV model according to (1), which is roughly two orders of magnitude faster than the other model. Its major deficiency is that it does not contain the radiation dependence of the efficiency and overestimates the module's MPP power. The relative error increases with decreasing radiation, while the absolute error has a maximum at 400 W/m^2 radiation. The annually predicted energy is almost 4 % higher than the result of the more reliable complex model. The overestimation is particularly disadvantageous since it shows the establishment of the PV system as a better investment than it really is. The simplified PV model provides less information to the DC circuit's and inverter's model, whereby it reduce the accuracy of these models as a subsidiary effect.

The choice of the appropriate simplification depends also on the specific objective of the calculation and the available processing capacity. For long-term analyses the most complex model is suggested, while for short-term predictions using some simplification may be worthwhile.

E. Dynamic behaviour

The presented models are applied for steady-state conditions and neglect the transients resulting from the changes of radiation and ambient temperature. In fact these meteorological conditions are changing in every moment of the day, thus the system never operates in steady-state. However, the static model is acceptable when the transient's time constant is much lower than the calculation intervals. Due to typically fast electric time constants the electric transients are negligible in the respect of energy production, the power changes of the module follows instantaneously the varying of radiation. The thermal processes are slow enough to influence the module's energy production, because of the slow change of the cell temperature and the dependent efficiency.

The prepared simulation was extended to take the PV module's dynamic behaviour into account and illustrate its effects. The air temperature can only change slowly due to the heat capacity of the atmosphere and land, but the radiation can vary fast and significantly while it becomes shaded by clouds. The performed calculation presents the suddenly decreasing and then increasing of the radiation, which represents a cloud crossing over a PV array. The electric time constant was neglected and the thermal time constant was selected to 6 minutes based on the module's heat capacity, surface and heat transfer coefficient derived from the NOCT temperature. The calculation was performed in one minute breakdown based on the time-dependent thermal differential equation of the module and the models of the PV system, the results are shown in Figure 6.

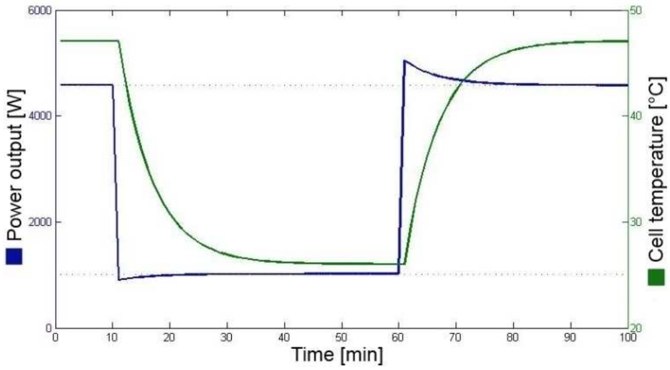

Fig. 6. Dynamic response of the PV system to instantaneous radiation changes

The radiation changes occur in the 10th and 60th minutes, between the 900 W/m^2 and 200 W/m^2 levels, at other times the radiation is constant to emphasize the transient effect. The power output changes simultaneously with the radiation but in greater extent than the difference between the steady-state values. The suddenly increasing radiation results a higher module power due to the still higher efficiency caused by the still lower cell temperature, then the power slowly decreases its steady-state value.

Although these transient conditions cause some energy production surplus, the dynamic behaviour has only an insignificant impact to the annual predictions; furthermore the meteorological databases with hourly data are anyway unsuitable for these purposes. The transients can play a greater role in short-term calculations, but the lower accuracy requirements allow us to neglect them. The quick changes in output power are important mostly in the aspect of the system integration. While examining the PV system's network effects it should be taken into account that the possible power jumps can exceed the potential steady-state power's difference.

F. Payback calculation

A simple method for calculating the payback period for PV systems is based on the net present value (NPV).

$$\boldsymbol{C_0 = c \cdot E \cdot \left(\frac{1}{r} - \frac{1}{r\cdot(1+r)^n}\right)} \tag{5}$$

Where c is the feed-in tariff (€/kWh), E is the annual energy production (kWh), r is the discount rate (-), n is the payback period in years and C_0 is the investment cost (€). Equation (5) is a very simplified formula but it is appropriate to present the most important factors of the economic feasibility.

The investment costs can be known exactly during the establishment of the system, the feed-in tariff is usually constant depending on the concluded agreement or the legal regulations. The only unknown parameter is the predicted energy production, that's why its accuracy has a great impact on the result. The discount rate or interest rate depends on the risk of the investment, and its lower values means faster return. The precise prediction of expected energy generation reduces the uncertainty and thereby the risk of the investment, which causes a shorter payback period and improve the feasibility of the project.

4. Conclusion

Using modern methods and computers enable us to simulate the photovoltaic systems with very good accuracy; where the biggest uncertainty of the prediction comes from the weather forecast. Different models were described and compared in aspects of accuracy and computation requirements for the cases of both short and long-term calculations. Long-term energy production predictions are used in payback estimations, while short-term calculations could be important in facilitating the system integration of PV plants. Annual energy prediction was performed to a specific PV system in a Hungarian site based on two different databases, where the high importance of the appropriate database selection was illustrated. The analysis of the system losses shown that the most of them occurred on the inverter and only a small portion dissipated on the DC wiring.

Illustrating the PV efficiency as a function of temperature and radiation has shown that both of them have a not negligible effect on the efficiency. The PV system have a fairly good efficiency in the full range of radiation, which means that they are suitable also for the poor radiation conditions unlike the other solar energy utilization methods, such as solar thermal power plants. Some PV system design principles, such as the inverter's optimal sizing were also mentioned supported with quantified simulation results. The simulation of the solar modules dynamic behaviour showed large power changes in case of a sudden shading, which is a disadvantage to the grid.

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