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Optimization of PV-based energy production by dynamic PV-panel/inverter configuration

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Introduction

This paper investigates the possible increase in annual energy production of a PV system with more than one MPPT (maximum power point tracker) input channels under Nordic illumination conditions, in case a concept of dynamic switching of the PV panels is used at the inputs of the inverters.

The power output of any photovoltaic (PV) system is affected not only by the irradiation level, but also by the conversion efficiency of the applied inverter. In cloudy weather, as in winter, the power generated by PV panels is fairly low compared to peak production. The inverters for a PV plant are dimensioned after the rated Wpeak value of the panels connected, but PV inverters typically have maximum conversion efficiency at a specific input power level. Thus, inverters will exhibit a conversion efficiency depending on the actual solar irradiation level. For low irradiation levels it thus seems beneficial to connect PV panels/strings in parallel to one MPPT input /inverter in order to utilize higher overall conversion efficiency. This method has been reported in literature [1] but has not yet been applied to Nordic illumination conditions, as far as we know.

Available data set

Meteorological data used in this study have been obtained from DMI (Danish Meteorological Institute). The data contain a "average year" for 2002, including the normal direct as well as the diffuse irradiation components, temperature etc. Especially in Nordic areas, long periods of bad and cloudy weather are expected , resulting in low conversion efficiency due to low power input. The same is the case at sunrise and sunset. See figures 1 and 2 for an example of varying irradiation over one year.

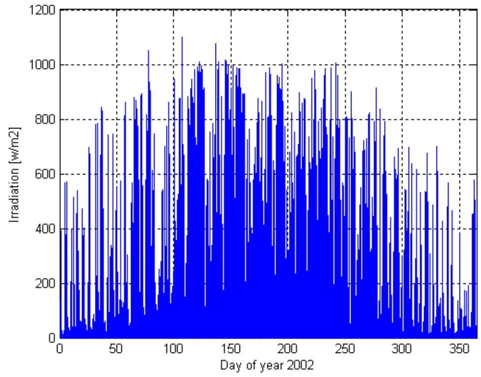

Figure 1. Direct irradiation profile for the "Danish average year 2002" [2]. Data sampled per hour.

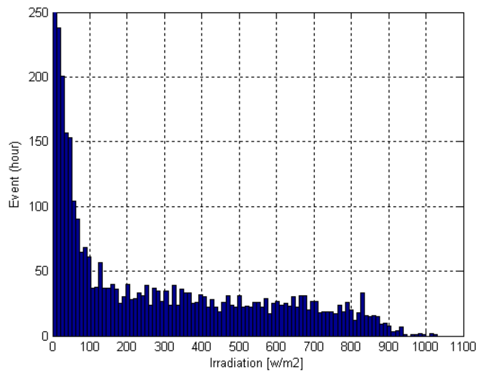

Figure 2. Histogram of the direct irradiation in the "Danish average year 2002". Night values=0 are not shown to scale.

Basic configuration

The concept investigated is based on the allocation of strings to specific MPPT-inputs, determined by the actual irradiation level. Optimum configuration is seen as the configuration at which the inverter operates with the highest conversion efficiency. The principle is illustrated in figure 3 by combining 3 strings.

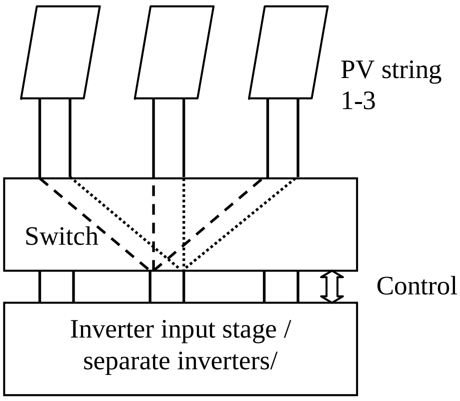

Figure 3. Principle of combining three PV-strings to increase annual power production

Irradiation profile

The virtual energy production for a 15 kW PV-system, consisting of 3x20 250W panels, has been simulated. This data set used in this study contains measurements of the normal direct and diffuse irradiation components on an hourly basis, as well as the position of the sun, temperature etc. Irradiation values must be adapted to the panel orientation in order to calculate the output power of the PV-panels. The approach followed here is based on [3]. See figure 4.

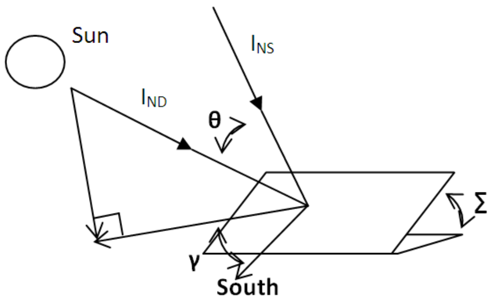

Figure 4. Panel coordinate system (after [8]).

Total solar radiation I_{TS} incident on the tilted surface can be expressed as a function of the received normal irradiation $I_{ND,}$ the angle of incidence relative to the surface θ the tilt angle ∑, the horizontal orientation γ and the ground albedo ρ. I_{TS} will consist of contributions from 3 sources; the direct sunlight I_{NS}, the diffuse radiation I_{DS} and the ground reflected diffuse radiation I_{RS}.

$$I_{TS} = I_{NS} + I_{DS} + I_{RS} \qquad (1)$$

I_{NS} can be determined by pure geometry

$$I_{NS} = I_{ND} \cos(\theta) \qquad (2)$$

where

$$\theta = \cos^{-1}[\sin(\beta)\cos(\Sigma) + \cos(\beta)\sin(\gamma)\sin(\Sigma)]$$

The addition of the diffuse irradiation component I_{DS} as well as the ground reflected radiation I_{RS} needs some consideration. A tilted surface facing the sun will in reality receive more diffuse light than if pointing in the opposite direction. Elaborate studies have been undertaken to investigate this anisotropic effect [4]. In this study the effect of diffuse light has been included through a simple model

$$I_{DS} = I_{diff} \cdot R_{diff} \qquad (3)$$

where R_{diff} is the diffuse transposition factor. For diffused light evenly distributed over the whole hemisphere R_{diff} can be expressed by a simple anisotropic approximation [3,4]

$$\mathrm{R_{diff}} = (1 + \cos(\Sigma))/2 \qquad (4)$$

Eq. 4 is applied in this study. For in-depth analysis of diffuse radiation modeling, model accuracy and literature reviews, see [4-6]. The ground reflected diffuse irradiation I_{RS} is determined by the measured total ground reflection E, the albedo value ρ and the ground transposition factor Rr.

$$I_{RS} = \rho \cdot \mathrm{E} \cdot R_r \qquad (5)$$

For an ideally isotropic surface, R_r can be expressed as

$$\mathrm{R_r} = (1 - \cos(\Sigma))/2 \qquad (6)$$

The problem is generally to determine E, which is often neglected in studies due to its rather small contribution. Ground reflections are not included in this study since available data sets do not include E, and in literature, the effect of ground reflection is considered to be minor [5].

Inverter efficiency curves

Overall inverter efficiency is commonly used as a sales parameter; the higher the better. In order to compare this sales parameter, specific procedures have been accepted by the EC and the Californian Energy Commission (CEC) for measurement of overall inverter efficiency [7]. Both procedures use a weighted ratio between efficiencies at specified power levels, relative to the nominal power. See Eq. 7-8 [7].

$$h_{EC} = 0.03h_{5\%} + 0.06h_{10\%} + 0.13h_{20\%} + 0.1h_{30\%} + 0.48h_{50\%} + 0.2h_{100\%} \quad (7)$$

$$h_{CEC} = 0.04h_{10\%} + 0.05h_{20\%} + 0.12h_{30\%} + 0.21h_{50\%} + 0.53h_{75\%} + 0.05h_{100\%} \quad (8)$$

It can be seen that the EC method includes the efficiency at lower power levels than the CEC standard, which has a higher weight for higher power levels. From a sales perspective, the EC method is therefore "better" for inverters intended for use in cloudy areas.

The efficiency curves for two typical inverters are shown below. It can be seen that the inverter efficiency drops off substantially at lower output power levels and it is thus anticipated that, when having a system with several inverters/inputs, an efficiency gain can be obtained by combining the inputs into one MPPT channel (and turn off the other MPPT channels). A detailed analysis will have to take the internal structure and different efficiencies of the sub-parts of a given inverter into account. This analysis only investigates an overall assumption based on a simple model.

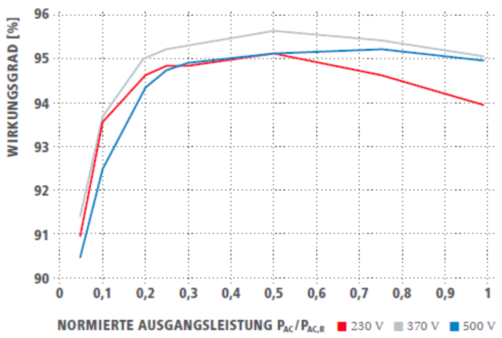

Figure 5. Inverter efficiency curves for an inverter of type Fronius IG Plus 150 V-3 [8].

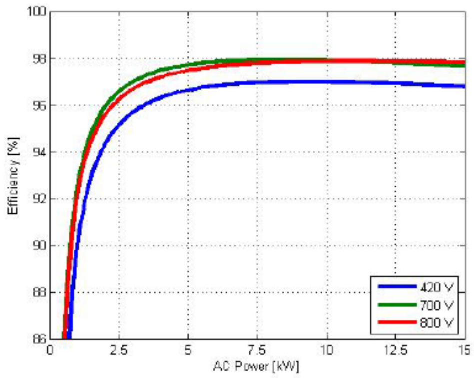

Figure 6. Inverter efficiency curves for an inverter of type Danfoss TrippleLynx CN 15 kW [9].

As demonstrated, the inverter efficiency depends on the actual output power with a characteristic decline of efficiency below 0.2 times the nominal power of the inverter to efficiency levels around 85%. For output power levels higher than 0.2 times nominal power, efficiency is in the range of 96-98%. The rapid decline in efficiency when operating below 0.2 times nominal power is due to the idle power losses in the inverter (control, switching etc.).

If output power is higher than the nominal power of the inverter, power production in the inverter will be limited to the rated maximum power of the input stage.

Simulation.

A 3-string system has been modeled in Matlab and the overall energy gain as a function of the threshold value for switching has been calculated. The simulation using the Danish data set is illustrated in figure 1 and models a system consisting of 3 strings with each 20 panels of 250W. Panel orientation is south, tilt is 37 degrees. A representative piecewise linear inverter efficiency curve, based on curves shown in figures 5 and 6, has been implemented. Since a rapid decline in inverter efficiency in general happens around a ratio of 0.2, it is expected that a potential gain in power production will happen around that level. A threshold value of 0.33 means that the PV-strings will be connected in parallel if the power from one string equals 1/3 the rated inverter power. A threshold above 0.33 implies that the inverter in operation might receive above its maximum power level and thus cannot utilize all potential power from the solar panels. A power temperature coefficient of -0.4%/°C has been included. The data set used contains ambient temperature measurement for each set of irradiation values, but, as they are not panel temperatures, they are not fully representative of the direct irradiation heating of the solar panels during warm periods. In the simulations this will result in a slightly higher power production during sunny periods than in a real test scenario. The curve shown in figure 7 can therefore be seen as a conservative estimate.

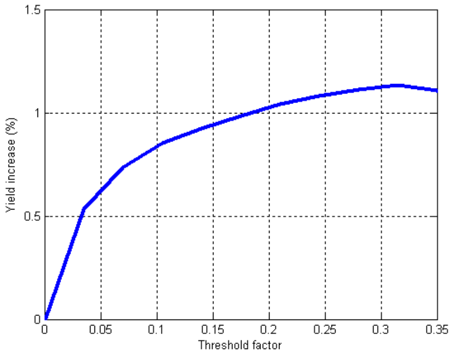

Figure 7. Simulated annual increase in power production by dynamic switching of 3x5kW strings between three inverters/inverter inputs.

In this study it is assumed that there is no power loss during the reconfiguration of the strings and that the inverter inputs behave as independent inverters. It can be seen that under the given simulation conditions an annual increase in power production in the rage of 1% is to be expected. This value compares well to tests described in literature, where a gain of around 1% is reached at a 123 kW test site in Dimbach, South-West Germany [1].

Conclusion and outlook

Based on data for a Danish average year, it has been shown that the annual power production of a solar plant under Nordic illumination conditions is expected to increase around 1% by applying dynamic switching of 3 strings of each 5 kW and a switching threshold level of 0.33. This work has been supported by the Sunrise-PV project, which is partly funded by Syddansk Vaekstforum in Denmark and the European Regional Development Fund.

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