Optimised Inverter Sizing in the UK

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Abstract

Optimal inverter sizing strategies in the UK are investigated in this paper, considering both the specific climate and the detailed inverter dynamic characteristics. A model of a PV system linked to an inverter is developed to assess and optimise how the different factors influence the correct sizing of a given PV system. Inverter efficiency changes up to 3% as a funtion of input voltage which needs to be considered in inverter sizing. The environmental data with time resolution higher than 10 minutes is recommended since low frequency data cannot guarantee accurate optimal sizing of inverter. Over-sizing the PV array rated power 10% to 40% with respect to the inverter nominal power appears to achieve the optimisation of inverter sizing in the UK.

Introduction

Photovoltaic systems produce direct current by converting light from the Sun into electricity which is then converted to alternating current by an inverter. The inverter may introduce significant losses in the overall system, which can be excluded by appropriate sizing. The sizing depends on detailed analysis of the inverter characteristics, environmental data and the module characteristics. It has been demonstrated [1-2] that the frequency of the measurements of the environmental data is of importance for this procedure while it does not necessarily affect the output of a PV module. Should the inverter be chosen too small with respect to the PV module rating, considerable energy losses will occur at high irradiance levels due to inverter clipping or the limited power output, which is required to avoid damage for the inverter. Whereas if the inverter is chosen too large, it will lead to low efficiency for average and low irradiances, which will increase the cost of the inverter and reduce the financial viability of any system [3]. This sizing will depend on the specifics of each location, and require optimisation on a case by case basis. This optimisation of inverter sizing is addressed in this paper by means of modelling. To date, in the UK only rules of thumb exist, which are, as this paper demonstrates, not necessarily correct as they depend on a number of parameters.

The model demonstrated here also considers the specifics of inverter operation. Typically, either a global inverter efficiency (such as the Euro-efficiency) or a relation between the efficiency and the ratio of applied power over rated power is used, but it is now recognised that one should include the effects of DC voltage as well [4]. The inverter efficiency always exhibits a specific dependence on both the input power as well as the input DC voltage. This results in a voltage window for achieving high efficiency which in most modelling approaches is not considered but would affect the system design significantly.

Methodology

A model of a PV system linked to an inverter is developed at CREST to assess and optimise how the different factors influence the correct sizing of a given PV system.

1) Horizontal Direct and Diffuse Irradiance

Environmental data used for modelling has been measured at CREST, Loughborough, UK for a whole year's period. The measurements of global irradiance on the horizontal plane are in 10-second time steps and module temperatures are in 10-minute steps. Erbs's model is employed to estimate the diffuse fraction from global irradiance [5], and then beam component is obtained accordingly.

2) In-plane Irradiance

With the direct and diffuse component of the irradiance on the horizontal plane and the time, location and orientation the total in-plane irradiance on the module surface can be calculated. Several possible ways to do so are described in [6]. According to the work presented on this conference [7], the Reindl's model has been chosen for this simulation for the specific site of Loughborough.

3) Modelling of IV Performance by King's Model

Using the module performance characteristics and the data developed above as input, the IV performance of a PV module can be modelled by employing a modified version of King's model, which is described in detail in [8]. From the IV performance of all components that make up the PV system the overall performance of the PV system can be calculated numerically, i.e. DC power and DC voltage. These can be further considered as the input data for an inverter.

4) Irradiance Weighted Efficiency

Using the inverter's characteristic data on DC/AC conversion efficiency (as a function of the input power and input voltage obtained above), which is provided by Arsenal Research, the AC power from the inverter can be calculated. The inverter's own consumption of DC power is included in the DC/AC conversion efficiency curve. Integration of the values of inverter output power over all time steps of the year results in the annual energy production of the PV system.

Thus, the annual DC/AC energy conversion efficiency is defined as:

$$\eta_{weighted} = \frac{\sum\limits_{time} \eta_{ins} \cdot G}{\sum\limits_{time} G} \qquad (1)$$

Where η_{ins} is the instantaneous inverter efficiency and G is the global irradiance in W/m^2 at every operating time step.

Effects of Inverter Dynamics

Typically, for estimating the size of inverter, either a global inverter efficiency (such as the Euro-efficiency) or a relation between the efficiency and the ratio of applied power over rated power (Non-voltage dependent efficiency) is used. For the inverter in this study, as shown in Figure-1, it highlights the importance of the inclusion of the voltage window into the modelling. This dynamic behaviour of the inverter is of great importance for system design since up to 3% efficiency change as function of DC voltage. Mathematically, non-voltage dependent inverter efficiency can be regarded as a 2-D function and defined as $\eta_n(P_{DC})$, a function of DC power only. Whereas, the voltage dependent inverter efficiency is treated as a 3-D function and defined as $\eta_v(P_{DC}, V_{DC})$, not only a function of DC power but also a function of DC voltage.

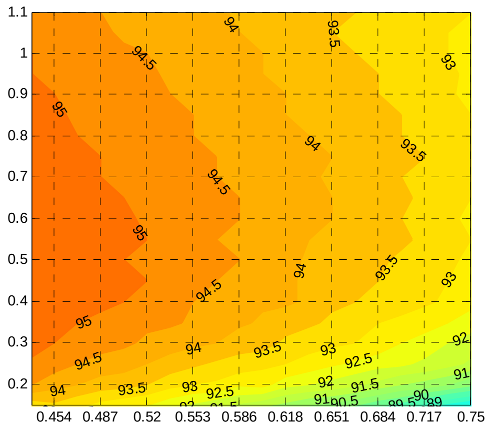

Figure 1: Voltage dependent inverter characteristics: inverter efficiency for different power and voltage levels

A model which is designed to calculate the $\eta_v(P_{DC}, V_{DC})$ is described in [4], and its dynamic characteristic information of inverter for this work is provided by Arsenal Research for current inverter.

This paper employs the 3-D inverter characteristics. Thus, the η_{ins} in equation (1) can be replaced by $\eta_v(P_{DC}, V_{DC})$. This is the basis for the investigation of optimal sizing for different module orientations and inclinations.

Effects of Time Steps

Typically, system sizing is carried out on hourly data sets but there is some debate that shorter time steps are required [2]. The UK is a slightly different environment (with large amount of diffuse component throughout the year) to the ones presented by others and thus the effects are demonstrated here. Within a period of one hour the irradiance can vary significantly, which might not be captured in the averages but will affect the inverter operation [2]. At low irradiance values, this can cause more start-ups in the inverter than expected based on hourly data sets, and thus losing energy. At high irradiances on the other hand, peak-shaving compared to hourly averages leads to an underestimation of the highest irradiance values and thus stronger and more frequent clipping at the inverter's maximum input power. Irradiances at large intensities are limited, especially occurrence of irradiance above 1kW/m^2 is mininal in the given data sets, which admittedly is based on one of the worst summers in history. There is a further effect on module temperature, which might also be significant, but has not been reported as widely as the effects of irradiance. This is apparent from Figure-2, where the average temperature for higher irradiances is much lower when considering instantaneous irradiances than when considering hourly sets. This signifies that in the infrequent high irradiance levels, the thermal equilibrium is not reached and thus the module is not fully heated and subsequently the temperature is lower.

A calculation is presented on the irradiance distribution for Loughborough using measured 10 second data and also using the same data condensed to 1 minute, 10 minutes and 1 hour. The data sets cover one complete year from Feburary 2005 to January 2006.

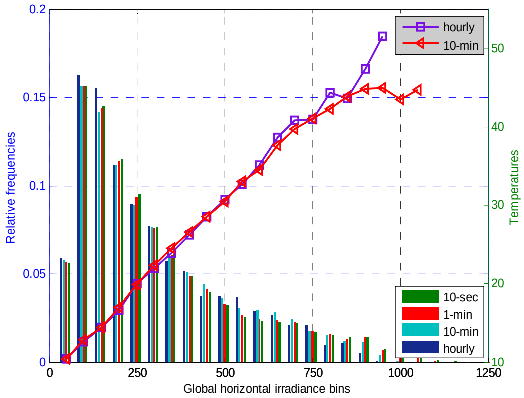

Figure 2: Distributions of global horizontal irradiance and module temperature

The cumulated relative frequencies of irradiance obtained above 750 W/m^2 in Loughborough are 19.98% (10 sec resolution), 18.75% (1 min resolution), 14.22% (10 min resolution) and 8.62% (1 hr resolution). This shows that the decrease of time scale from 10 seconds to 1 minute is not significant but that a further decrease to 10 minutes or 1 hour is significant. It is also seen that the use of hourly data overestimates the temperature by about 10°C for high irradiances, which will impact significantly on the inverter sizing, as the voltage applied to the inverter will be on average higher than one would expect based on the hourly simulations.

Results and Discussion

Simulation has been done by investigating the optimum PV array configuration for a specific inverter. Then evaluation is carried out based on the annual DC/AC energy conversion efficiency. Finally, the the optimum sizing ratio is given in terms of $P_{DC,STC}/P_{inv,rated}$ and $V_{mpp,STC}/V_{inv,max}$ for different orientation and inclination.

For a specific inverter with the characteristics as shown in Figure-1, the results of annual DC/AC energy conversion efficiency for different array configurations are shown in Figure-3, where Y-axis represents total number of modules in series and X-axis is the total number of module strings in parallel. The modules used for this simulation is the BP monocristalline, which is small modules used to achieve a high resolution. Figure-4 selects four different $V_{mpp,STC}/V_{inv,max}$ ratios (as defined by the number of modules in series) and plots annual DC/AC energy conversion efficiency versus $P_{DC,STC}/P_{Inv,Rated}$ (which is then defined by the number of module strings in parallel). The maximum annual efficiency is achieved for ratios of $V_{mpp,STC}/V_{inv,max}$ and $P_{DC,STC}/P_{inv,rated}$ are around 0.6-0.7 and 1.1-1.4, respectively, i.e. over-sizing the PV array power 10-40% with respect to inverter nominal power. The currently suggested sizing ratio in the UK is oversizing 30%, i.e. the rated power of the inverter is 75% of the rated power of the PV array, so broadly in correct range if the system voltage is chosen correctly.

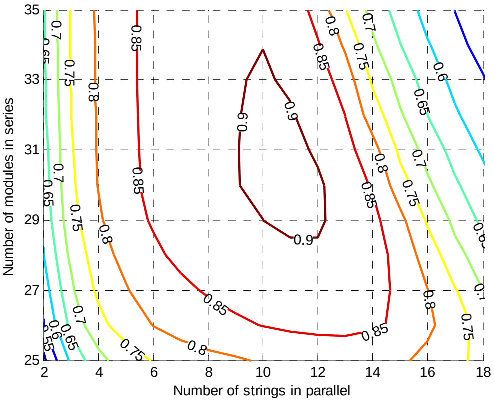

Figure 3: Annual DC/AC energy conversion efficiency for different PV array configurations

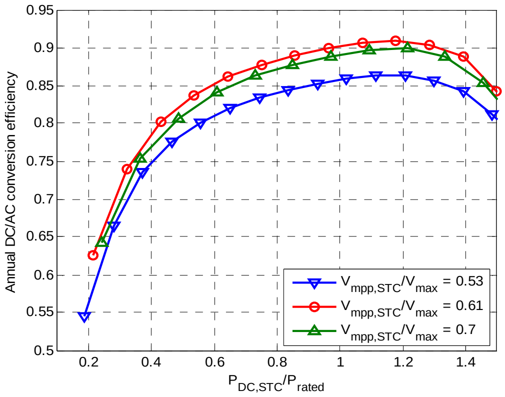

Figure 4: Annual DC/AC energy conversion efficiency for selected $V_{mpp,STC}/V_{inv,max}$ ratios

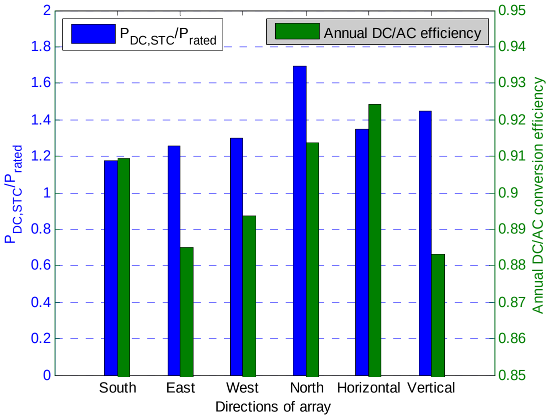

Figure 5: Optimum inverter sizing ratios and annual DC/AC energy conversion efficiency for different array orientations and inclinations

Figure-5 shows the optimum $P_{DC,STC}/P_{inv,rated}$ ratios for different PV array orientations and inclinations, i.e. modules with 45° elevation angle and facing south, east, west and north, respectively, as well as with 0° (horizontal), 90° (vertical) elevation angle facing south. South facing modules clearly collect more irradiance, which results in a relatively low $P_{DC,STC}/P_{inv,rated}$ ratios. As the orientation of the PV array changes away from its ideal condition, the incident irradiance is reduced, resulting in increasing sizing ratios for optimum inverter sizing. The most extreme case, the north facing system, might sound very artificial but there are systems in the UK with near-north orientation. The obtained annual DC/AC energy conversion efficiencies for different directions (shown in Figure-5 as the second Y-axis) are between 88.5% and 92.5%, while the Euro-efficiencies for the same voltage levels are between 92.9% and 93.8%. For instance, the efficiency for south facing system is 90.9%, which is 2 % lower than the Euro-efficiency 92.9%. The inverter's property of maximum efficiency occuring at the low limit of input DC volatge makes system with less ideal direction might have a higher energy efficiency possible.

Conclusion

The effects of time resolutions and inverter dynamic characteristics on optimum inverter sizing have been investigated in this paper and validated by simulation. Up to 3% inverter efficiency change as a funtion of voltage which needs to be considered in inverter sizing. The environmental data with time resolution higher than 10 minutes is recommended since low frequency data cannot guarantee accurate optimal sizing of inverter. The recommended guidelines for optimum inverter sizing is over-sizing the PV array 10% to 40% with respect to the inverter nominal power. This is different from the 130% rating given by the current guidelines specific to this inverter type. However, suboptimal orientation will require increased size of $P_{DC,STC}/P_{inv,rated}$, which in extreme cases can be as much as 170% (north facing system). Fortunately, the losses due to suboptimal sizing are not too significant in the case investigated, as it is shown the efficiency for the given inverter are between 88.5% and 92.5% on an annual basis for all orientations.

Acknowledgements

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