EFFECT OF MODULE DEGRADATION ON INVERTER SIZING

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ABSTRACT

The effect of amorphous Silicon (a-Si) module degradation on inverter sizing is investigated in this paper to identify appropriate sizing ratios even if only undegraded data-sheet values are available. The seasonal degradation and annealing pattern of a-Si modules requires special attention to the sizing of inverters for these devices, as is demonstrated in this paper for three types of modules with different degradation rates. The efficiency of the inverters depends on the sizing ratio as well as the DC input voltage. Here data of an inverter with relatively dependence on operating voltage is used. As modules degrade, the optimum ratio of system rated power with respect to inverter nominal power increases by 10 to 15% for the specific inverter. Considering the module life-time, the inverter size chosen to be matched to the degraded power and voltage rating achieves high efficiency over the life-time of the modules, while the inverter chosen to match initial values, as given by some manufacturers on their datasheets, can add about ten percent losses to the operation.

INTRODUCTION

A major demonstration programme for large scale systems has been completed in the UK with an extensive monitoring campaign associated with several installations. The inverter sizing was identified in some systems as problematic, despite most systems being designed following the best practice given by the UK trade organisation (PV-UK) as sizing the inverter at 75% of the DC array. There currently is an argument if this ratio should be lowered or increased. The proponents of the first argue that the contribution of light conditions to the overall energy production is unusually low in the UK, while the proponents of the second thesis argue that the typical datasets of one-hourly data severely underestimates the high irradiance contribution, as e.g. suggested by [1]. It seems that the second thesis is closer to the truth as shown by the authors [2]. It was suggested that the undersizing should be increased to 85%, which slightly increases overall system efficiency.

One unfortunate feature of this demonstration programme was that the thin film systems did perform well below the average, see e.g. [3]. The conclusion that this has to do with the material is obvious, but when investigating similar modules in long term testing [4], one could not detect severe underperformance on site. Also the inverters in these systems are well known and have been operated successfully with thin film modules in the past. Also sizing was carried out according to UK guidelines.

The thesis of this paper is that the additional underperformance could be due to the idiosyncracies of amorphous silicon based modules, which are known to degrade over the first six months or so of their life and then follow a stable seasonal pattern which is a mirror image of that of crystalline silicon devices, in that maximum efficiency is achieved in the summer time rather than winter [5].

The sizing depends on detailed analysis of the inverter characteristics, high frequency environmental data and the photovoltaic (PV) module characteristics. To allow for this a model was developed, using realistic input data from module-monitoring at the Centre for Renewable Energy Technology (CREST) and detailed inverter measurements taken at Arsenal Research.

In the following, first the model is described, then the input data is characterised to finally arrive at the impact of degradation on inverter sizing.

MODEL DEVELOPMENT

A model of an inverter linked to a PV system has been developed by CREST, which is depicted in Figure 1, to carry out modelling work to evaluate the effect of degradation.

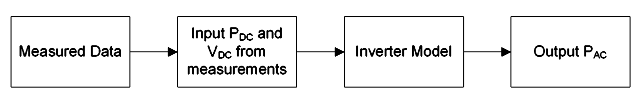

Figure 1: System model

The data for this study are taken from long term measurements conducted by CREST at Loughborough University, UK. The system carries out full I-V scans and measures in-plane irradiance as well as module temperature in 10-minute intervals for a variety of different a-Si modules, here the data of two single-junction and one double-junction modules are used. Devices operate since June 2001, July 2001 and October 2004, respectively. The

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inverter characteristics were provided by Arsenal Research, Austria.

The data used for modelling are chosen from the measurements above that between sunrise and sunset. Since the start date of each module is not in the same month, the first 24 months' data starting from its initial state after installation are used. The terms Year 1 and Year 2 used in following part of this paper indicate the first and the second 12-month periods of time. The measured voltage V_{DC} and power P_{DC} data are regarded as input for inverter model; the output of this model is the generated P_{AC}. The inverter's own consumption of DC power is included in the DC/AC conversion efficiency. Integration of the values of inverter output power over all time steps of a year or a month results in the annual/monthly energy production of the PV system.

The annual DC/AC energy conversion efficiency is defined as:

$$\eta_{weighted} = \frac{\sum_{time} \eta_{ins} \cdot G}{\sum_{time} G} \quad (1)$$

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

AMORPHOUS SILICON MODULE DEGRADATION

Generally, a-Si modules degrade significantly in first few months of operation and then fall into a seasonal annealing and degradation pattern. Following the initial degradation, one can assume stable operation, with long-term degradation being comparable to that of crystalline silicon, i.e. not more then 1%. This section reviews this, for the two extreme cases used in this study. Module 1 is a single junction a-Si module with high degradation rate, which was installed in July 2001. Module 3 installed in October 2004 is a double junction module with low degradation.

This device characteristics are reviewed by using data from each month to calculate the specific parameters (fill factor FF, V_{MPP}/V_{OC}, V_{MPP} normalised to the first month's value, I_{SC}/G normalised to the first month's value, and P_{MPP} normalised to the first month's value) shown in Figure 2 and Figure 3. The parameters shown in Figure 2 and 3 are calculated only for irradiances ranging from 950W/m^2 to 1050W/m^2. It tends to be difficult to find suitable data in Winter, explaining some 'missing' points in the figures. All the data are corrected to the reference temperature 25 °C using the temperature coefficients of module provided by manufactures.

The FF has been shown to be a likely indicator of the stabilized state of a-Si modules [6]. It exhibits significant degradation in the first months of operation before a relatively minor recovery/degration patter from Summer to Winter, indicating that the overall contribution of seasonal annealing is relatively minor in the UK. The I_{SC}/G ratio is an indicator that the main changes will be in the quality of the irradiance, namely spectral variations, which agrees with previous findings [7]. The voltage degrades significantly in first couple of months, but stabilizes after initial degradation, supporting the claim of low seasonal annealing in the UK. The main impact of these changes on long term behaviour will be from the two parameters energy (power) and voltage, as these are the inputs for the inverter performance model.

Comparing power and voltage variation of the two modules, they behave quite differently. Module 1 has the largest degradation that the normalized power at maximum power point degrades to 0.6 after operation and then exhibits a seasonal variation between 0.6 and 0.8 of its initial values. Its normalized voltage degrades 10% to 0.9, and then exhibits a small fluctuation afterwards. Module 3 shows a low degradation rate with power degrades around 8% and voltage around 4%. This, however, does not mean that the module degrades by only 8% but is an idiosyncracy due to the installation time, where the initial operation is close to winter and the initial degradation will not be completed fully at its first minimum, thus masking some of the effects normally seen in the initial degradation.

This issue of a-Si module seasonal degradation due to light exposure and subsequent thermal annealing has been addressed in the past authors but its feedback to the inverter has not been investigated to date. This degradation effect is usually ignored for sizing of inverter to a certain PV system, but later it will be shown that it can result in considerable energy losses, especially as some manufacturers actually give undegraded data of a-Si module on their datasheet.

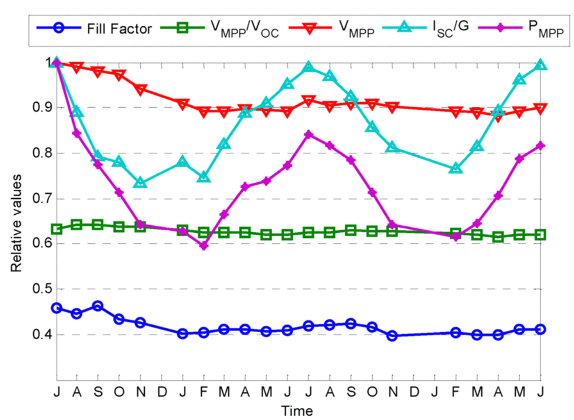

Figure 2: Specific parameters for the first two years of operation of Module 1

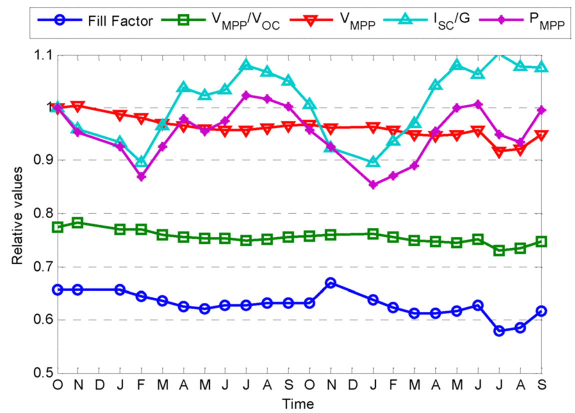

Figure 3: Specific parameters for the first two years of operation of Module 3

INVERTER DYNAMIC CHARACTERISTICS

Typically, for sizing of inverters, 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. 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 irradiance levels, which will increase the cost of the inverter and reduce the financial viability of any system.

Over the last years, there are many reports that [8] inverter efficiency 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 that in most modelling approaches has not been considered, which may not be the highest allowable voltage. The characteristics used in this study are shown in Figure 4. It highlights the importance of the inclusion of the voltage window into the modelling as it can cause up to 3% efficiency change as function of DC voltage, which is more than typically expected due to cabling losses in a PV system.

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. The voltage dependent inverter efficiency is treated as a 3-D function and defined as $\eta_d(P_{DC},V_{DC})$ surface. This paper employs the 3-D inverter characteristics. Thus, the η_{ins} in equation (1) should be replaced by $\eta_v(P_{DC},V_{DC})$.

The voltage dependence is even more relevant, because the seasonal variation of the operating voltage of an a-Si array is quite different to that of a c-Si module, as there are gains in voltage in Summer and not like a reduction in the case of c-Si modules. This is because of the low temperature dependence of a-Si modules causing only a relatively small reduction in the operating voltage which is counteracted by a gain due to seasonal annealing.

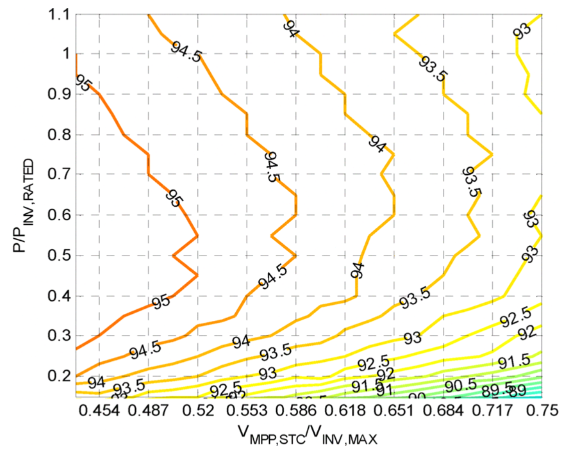

Figure 4: Inverter efficiency for different level of power and voltage

DEGRADATION EFFECT ON INVERTER SIZING

For different types of a-Si modules, the degradation rates are significantly different. Simulations are carried out to compare the annual DC/AC energy conversion efficiency for different modules at Year 1 and Year 2. Then evaluation is carried out based on the high power and low power energy losses.

Energy Conversion Efficiency for Different System Configurations

The results of annual DC/AC energy conversion efficiencyfor different array configurations are shown in Figure 5 to Figure 10 (For both Year 1 and Year 2). It is difficult to 'scale' an inverter and thus different parallel and series connection schemes are investigated, based on the modules in CREST's module monitoring stand. The caveat here is that each module has different power ratings and as such the results are not entirely comparable. The Y-axis represents the number of modules in series and X-axis is the number of module strings in parallel.

Figure 5 and 6 demonstrate the first and second year's energy conversion efficiencies of Module 1 that is the high degradation case. The large area in the central for Year 1 indicates the efficiencies above 80%, whereas the central area for Year 2 is the efficiencies above 90%. There is 10% difference in efficiency between Year 1 and Year 2, the reasons for this are investigated later.

Similar trends are seen for Module 2 and Module 3. However, as the degradation rates of Module 2 and Module 3 are much lower than that of Module 1, the difference of efficiency behaviour between Year 1 and Year 2 are smaller.

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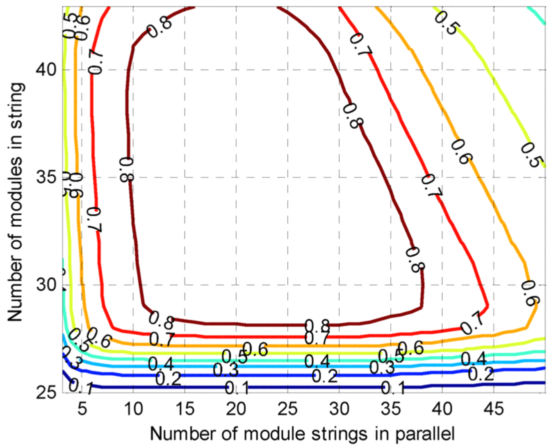

Figure 5: Annual DC/AC efficiency of Module 1 for different system configurations (Year 1)

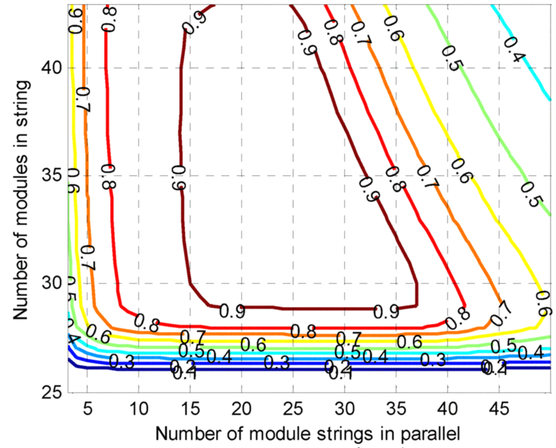

Figure 6: Annual DC/AC efficiency of Module 1 for different system configurations (Year 2)

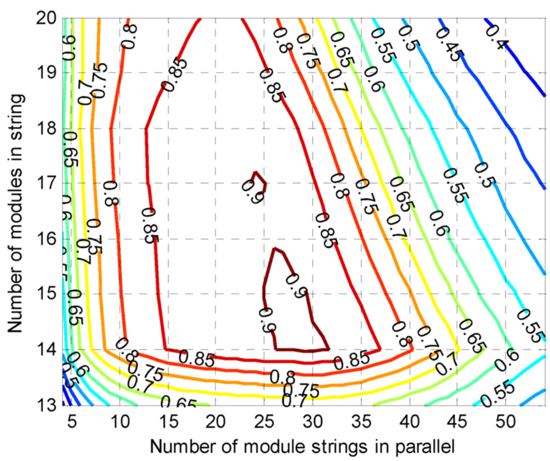

Figure 7: Annual DC/AC efficiency of Module 2 for different system configurations (Year 1)

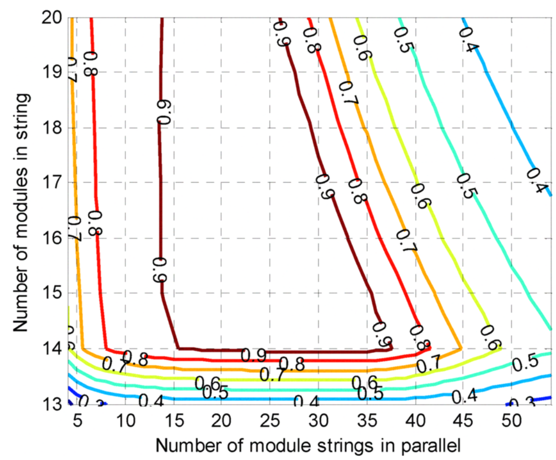

Figure 8: Annual DC/AC efficiency of Module 2 for different system configurations (Year 2)

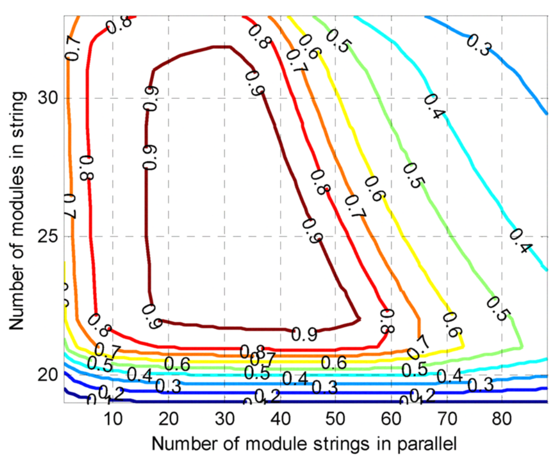

Figure 9: Annual DC/AC efficiency of Module 3 for different system configurations (Year 1)

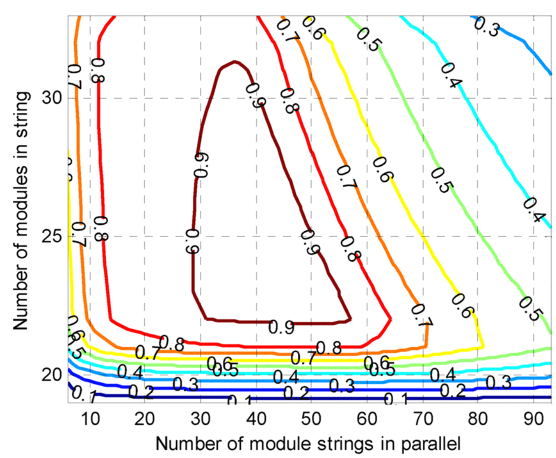

Figure 10: Annual DC/AC efficiency of Module 3 for different system configurations (Year 2)

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The behaviour of the low degrading modules is largely similar between single and double junctions. The degradation of the double junction may be slightly lower but this does not have any significant effect on the inverter sizing.

The results above are translated to the more familiar $P_{DC,STC}/P_{RATED}$ numbers in Figure 11, where one voltage level that goes through the central area where the high efficiency occurs, is selected for each module and a cross-cut through the efficiency matrix.is presented. It also can be found that the optimum sizing of inverter $P_{DC,STC}/P_{RATED}$ ratios for Module 1 are 1.1 in Year 1 and 1.3 in Year 2 (which means the optimum inverter nominal power with respect to PV system rating $P_{RATED}/P_{DC,STC}$ decreases from 0.9 to 0.75), for Module 2 are 1.05 in Year 1 and 1.2 in Year 2 ($P_{RATED}/P_{DC,STC}$ decreases from 0.95 to 0.8) and for Module 3 are around 1.0 for both Year 1 and Year 2 ($P_{RATED}/P_{DC,STC}$ remains 1.0). Therefore, to optimise the inverter sizing, the ratio of $P_{DC,STC}/P_{RATED}$ for module with high degradation rate has to be increased by 10-15%. As the degradation rate decreases, the increment in $P_{DC,STC}/P_{RATED}$ is becoming smaller.

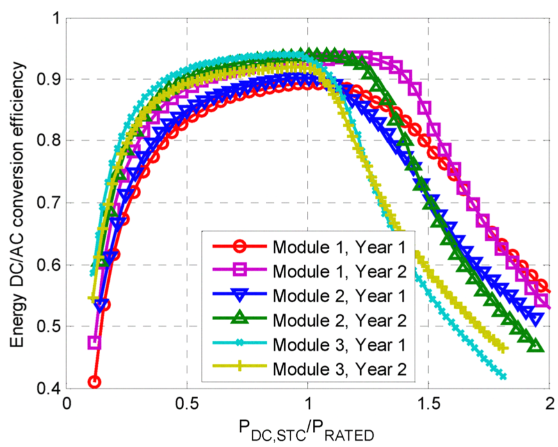

Figure 11: Annual DC/AC energy conversion efficiency for different types of new/degraded modules

Energy Losses Due to Low and High Input Power

The operating efficiencies appear a bit low when compared to the matrix shown in Figure 4 and thus the reasons of this efficiency reduction should be investigated. There are two main mechanisms to lose power: either the input DC power is lower than the allowed inverter minimal input power and the inverter switches off or the input power is higher than the allowed inverter maximal power, where the inverter has to be switched off to protect itself[1].

[1] In this study a complete switch-off is assumed, which is realistic for the inverter under investigation. Other inverters will loose less power at high irradiances due to voltage regulation.

Figure 12 demonstrates the energy losses due to inverter shut-off at low irradiance levels. The losses decrease with increasing $P_{DC,STC}/P_{RATED}$ ratio, which means that as the input power increases shut offs are less likely. Module 1 has the largest losses, followed by Module 2 and Module 3. This is an expression of the different low light behaviour of these modules, with the high degradation module also having the worst low light behaviour, causing high start-up losses.

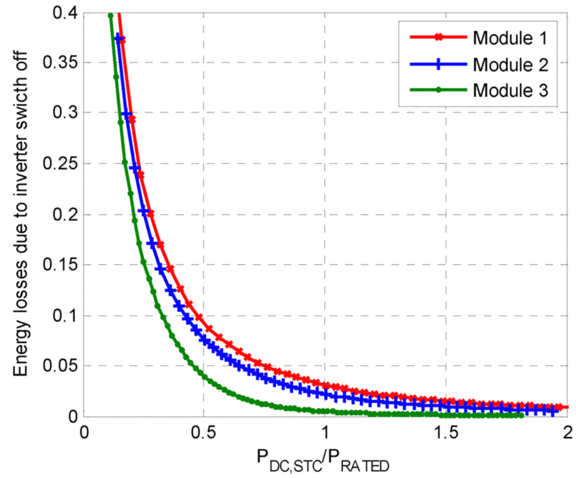

Figure 12: Energy losses due to low input DC power

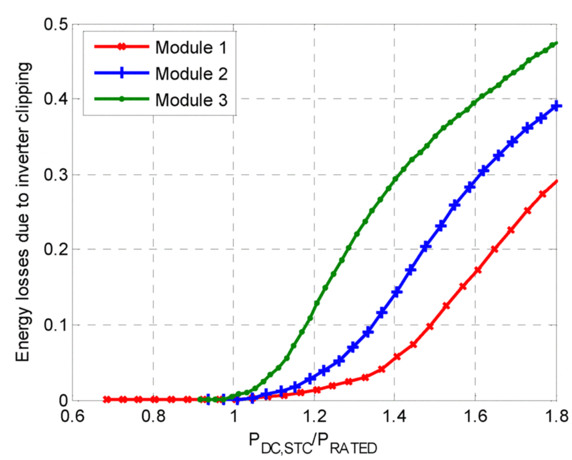

Figure 13: Energy losses due to high input DC power

Figure 13 demonstrates the energy losses due to inverter clipping effect at high irradiance levels. The losses increase with increasing $P_{DC,STC}/P_{RATED}$ ratio, especially when input power is greater than the rated power of inverter. Module 3 has the largest losses, followed by Module 2 and Module 1, which indicates that module with low degradation rate, has degraded less in power itself, and then lost more due to inverter clipping.

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CONCLUSIONS

The significance of a-Si module degradation on inverter sizing is investigated in this paper. A cross section of amorphous silicon modules was used to quantify possible losses due to sizing to the incorrect state. Module degradation causes the optimum ratio of system rated power over inverter rated power to increases by 10 – 15% for the specific inverter, otherwise resulting in additional energy losses in the range of 3-10%. The effect is most prominent for modules with high degradation because they not only lose the maximum power but also tend to exhibit the worst low light performance, causing a significant number of additional inverter shutdowns due to low input power.. It is also demonstrated that the voltage degradation of modules can have an effect on inverter performance, which for the given example favours mid-range voltages. The inverter size must be matched to the degraded module power and voltage rating, and will then have a respectable performance..

ACKNOWLEGEMENTS

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